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DESEMPENHO AMBIENTAL DA INDÚSTRIA DE CIMENTO PORTLAND POR MEIO DA AVALIAÇÃO DE CICLO DE VIDA: TRÊS ESTUDOS DE CASO

Tese submetida ao Programa de Pós-Graduação em Ciência e Engenharia de Materiais da Universidade Federal de Santa Catarina para a obtenção do Grau de Doutor em Ciência e Engenharia de Materiais

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Esta Tese foi julgada adequada para obtenção do Título de "Doutora" e aprovada em sua forma final pelo Programa de Pós-Graduação em Ciência e Engenharia de Materiais.

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A Deus, inteligência suprema e causa primeira de todas as coisas.

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“Por vezes sentimos que aquilo que fazemos
não é senão uma gota de água no mar.
Mas o mar seria menor se lhe
faltasse uma gota”.

Madre Teresa de Calcutá

RESUMO

Neste trabalho estudaram-se os impactos ambientais da produção de cimento por meio da metodologia de Avaliação de Ciclo de Vida (ACV), com o objetivo de avaliar a produção no Brasil em comparação com a produção na Europa e identificar oportunidades de melhoria. Para tanto, foram selecionados três cenários: “Empresa Europa” – baseado em dados primários de uma empresa com produção representativa de cimento tipo CP I localizada no sul da Europa; “Empresa Brasil” – baseado em dados primários de uma empresa brasileira com produção significativa de cimento tipo CP II e CP IV; e “Estimativa Brasil” – baseado em dados gerais da produção nacional de cimento e na legislação vigente. O ano base do estudo foi 2013 e foram utilizadas as metodologias de avaliação de impacto CML 2001 e Recipe. Também foi utilizado o banco de dados Ecoinvent e o software Simapro. Foram consideradas categorias de impactos atmosféricos, como “Mudanças Climáticas”, depleção de recursos, como “Depleção de Metais” e “Depleção de Fósseis” e categorias de toxicidade como “Toxicidade Humana” e “Ecotoxicidade”. Por ser um trabalho baseado na aquisição e interpretação de dados, a falta de alguns dados ou mesmo a estimativa desses dados faltantes influencia diretamente os resultados finais. Em todos os cenários, os processos de produção foram divididos em: (i) obtenção de matérias primas, (ii) obtenção de combustíveis fósseis, (iii) geração e uso de energia elétrica e (iv) clinquerização. Para os cenários “Empresa Europa” e “Empresa Brasil”, a etapa de transportes também foi estudada. As análises dos impactos para o cenário “Empresa Europa” foram realizadas com base nos métodos CML 2001 e Recipe. O primeiro método foi utilizado para gerar comparabilidade com outros estudos já desenvolvidos para a região. Já o método Recipe, cientificamente mais aceito, foi utilizado no cenário europeu e nos demais cenários analisados. Apesar das diferenças entre os métodos, as conclusões em geral não se alteram: as emissões do forno, a geração e uso de energia elétrica e a obtenção de combustíveis fósseis, nessa ordem, são os principais contribuintes para as categorias de impacto analisadas. No cenário “Estimativa Brasil”, o principal contribuinte para a categoria de impacto Mudanças Climáticas é, como esperado, emissão atmosférica do processo. Essas emissões também contribuem significativamente com a formação de oxidantes fotoquímicos, material particulado, acidificação, eutrofização marinha e toxicidade humana. Exceto para depleção de metais, todas as outras categorias são afetadas, principalmente, pela extração de combustíveis fósseis. Para o cenário "Empresa Brasil", encontrou-se que a etapa de Transportes é a que mais contribui para todas as categorias de impacto analisada. Isso ocorre devido ao fato de que o modal rodoviário é o principal no país. Além disso, o consumo de combustíveis fósseis no forno da empresa também representa uma das etapas mais impactantes do processo, de modo que a substituição desses fósseis por combustíveis alternativos pode levar a ganhos ambientais, desde que sejam levadas em consideração as distâncias a ser percorridas por estes alternos. Em todos os cenários, a geração de eletricidade foi baseada nos dados disponíveis no banco de dados Ecoinvent. Entretanto, para verificação, os três cenários foram reanalisados com base na geração de eletricidade para o ano de 2013. Verificou-se que não houve alteração significativa para os cenários brasileiros, mas o cenário europeu teve os impactos reduzidos. Isso deve-se ao fato de que o Brasil vem fazendo uso de energias derivadas de combustíveis fósseis, como as termelétricas, ao contrário do que ocorre no cenário Europeu, onde o uso de energias alternativas está cada vez mais presente. Por fim, realizou-se a normalização de todos os impactos estudados segundo o método Recipe, para todos os cenários. Verificou-se que o cenário Europeu apresenta os menores impactos em relação aos cenários nacionais e demonstrou-se a importante contribuição da etapa de transportes para a geração de impactos ambientais nos cenários brasileiros.

Palavras-chave: cimento, ACV, Brasil, Europa.

ABSTRACT

In this study, we assessed the environmental impacts of cement production through Life Cycle Assessment (LCA), in order to evaluate production in Brazil compared to production in Europe and identify opportunities for improvement. We selected three scenarios: "European Plant" - based on primary data from a company with representative production of cement type CP I located in southern Europe; "Brazilian Plant" - based on primary data from a Brazilian company with significant production of cement type CP II and IV; and "Brazilian Estimative" - based on general data of the national production of cement and current legislation. The base year of the study was 2013, and we used the impact assessment methodologies CML 2001 and Recipe. Ecoinvent database and the software SimaPro were employed. We considered impact categories of atmospheric impacts such as “Climate Change”, resource depletion such as “Metal Depletion” and “Fossil Depletion” and toxicity categories as “Human Toxicity” and “Ecotoxicity”. Because it is a work based on acquisition and interpretation of data, the lack of some data or even estimating these missing data directly influences the final results. In all scenarios, the production processes were divided into five steps: (i) raw materials obtaining, (ii) fossil fuels obtaining, (iii) electricity use and (iv) clinkering. For “European Plant” and “Brazilian Plant”, the transport step was also studied. Analyses of the “European Plant” were based on CML 2001 and Recipe. The first method was used to generate comparability with other studies already developed for the region. However, Recipe method is most scientifically accepted. Due to that, all further analysis were conducted based on it. Despite the differences between the methods, findings generally do not change: kiln emissions, the generation and use of electricity and fossil fuels obtaining, in that order, are the main contributors to the impact categories analyzed. In the "Brazilian Estimative", the main contributor to “Climate Change” impact category is, as expected, the clinkering. These emissions also contribute significantly to the “Photochemical Oxidants Formation”, “Particulate Matter”, “Acidification”, “Marine Eutrophication” and “Human Toxicity”. Except for “Depletion of Metals”, all other categories are affected mainly by the extraction of fossil fuels. For the scenario “Brazilian Plant”, it was found that the transport stage is the largest contributor to all categories of impact analyzed. This is due to the fact that transports are mainly by road in the country. Moreover, the consumption of fossil fuels in the kiln also represents one of the most impactful process steps. Due to this, the replacement by alternative fuels may lead to environmental benefits; however, the distances to be traveled by these alternatives must be taken in account. In all scenarios, the electricity generation was based on data available in Ecoinvent database. Nevertheless, for verification, the three scenarios were re-analyzed based on the generation of electricity for the year 2013. There was no significant change to the Brazilian scenarios, but the European scene presented reduced impacts. This is because Brazil has been making use of energy derived from fossil fuels such as thermal power, contrary to what occurs in the European scenario, where the use of renewable energy is increasingly present. Finally, we conducted the normalization of all studied impacts according to Recipe method to all scenarios. The European scenario has the lowest impacts in relation to Brazilian scenarios and the importance of transport step to all impact categories was demonstrated.

Keywords: cement, LCA, Brazil, Europe.

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LISTA DE ABREVIATURAS E SIGLAS

ACV	Avaliação de Ciclo de Vida
ADP	*Abiotic Depletion Potential*
AP	*Acidification Potential*
BAT	*Best Available Techniques*
CANACEM	*Cámara Nacional del Cemento*
CAS	*Chemical Abstract Service*
CC	*Climate Change*
Cembureau	*The European Cement Association*
CONAMA	Conselho Nacional do Meio Ambiente
CSI	*Cement Sustainability Initiative*
EP	*Eutrophication Potential*
EU	*European Union*
FD	*Fossil Depletion*
FET	*Freshwater Ecotoxicity*
FICEM	*Federación Interamericana del Cemento*
GWP	*Global Warming Potential*
HT	*Human Toxicity*
IPCC	*International Panel on Climate Change*
ISO	*International Standard Organization*
LCA	*Life Cycle Assessment*
LCIA	*Life Cycle Impact Assessment*
MD	*Metal Depletion*
ME	*Marine Eutrophication*
MET	*Marine Ecotoxicity*
OD	*Ozone Depletion*
PMF	*Particulate Matter Formation*
POF	*Photochemical oxidant formation*
POP	*Photochemical oxidant potential*
RDF	*Residue Derived Fuel*
TA	*Terrestrial Acidification*

TE	*Terrestrial Eutrophication*
TET	*Terrestrial EcoToxicity*
WBCSD	*World Business Council for Sustainable Development*

SUMÁRIO

1. INTRODUÇÃO

A palavra cimento é originada do latim *caementu*, que na antiga Roma designava uma espécie de pedra natural de rochedos não esquadrejada (quebrada). No final do século XVIII cientistas e pesquisadores europeus se dedicaram à descoberta de uma fórmula ideal para o desenvolvimento do cimento hidráulico, ou seja, um material que reage e endurece na presença de água. Foi assim que, em meados de 1830, o processo de obtenção do Cimento Portland foi patenteado. A partir daí, seu uso e sua comercialização cresceram de forma gradativa em todo o mundo (ABCP, 2002; SNIC, 2011).

No ano de 2014, a produção mundial de cimento foi estimada em 4,3 bilhões de toneladas, porém é importante considerar que a produção de cimento está ligada à atividade econômica de um país e o nível de industrialização e desenvolvimento de infraestrutura local (Pacheco-Torgal et al., 2014). Desta maneira, a China é responsável por mais de 50% desse montante. Na Europa, a produção de cimento vem se mantendo constante nos últimos anos, em torno de 160 milhões de toneladas/ano. No Brasil, a produção tem aumentado a cada ano, culminando em mais de 70 milhões de toneladas no ano de 2014 (Cembureau, 2014).

Essa expressiva produção de cimento envolve o uso de grandes quantidades de matérias primas e combustíveis fósseis e/ou alternativos, estando, portanto, associada à severos impactos ambientais. Estima-se que para a produção de 1 tonelada de cimento Portland, sejam utilizadas mais de 1,4 toneladas de matérias primas, em torno de 110 kwh de energia elétrica e de 60 a 130 kg de combustíveis (Huntzinger and Eatmon, 2009; Lamas et al., 2013).

Os principais impactos ambientais associados à esta atividade estão relacionados a emissões de poluentes atmosféricos, como CO_2, SO_2, NO_x, material particulado e outros, como metais pesados e dioxinas. Nesse contexto, significantes esforços vêm sendo realizados em vista ao controle e mitigação dessas emissões.

Um desses esforços é a implementação da técnica de coprocessamento, que consiste em substituir matérias primas e combustíveis fósseis por materiais alternativos. Essa ação já é praticada com sucesso na Europa, especialmente em países como Holanda, Alemanha e Noruega (Aranda Usón et al., 2013). No Brasil, o coprocessamento foi implementado no início dos anos 90, no entanto, ainda ocorre de forma incipiente no país (Rocha et al., 2011). Em algumas fábricas europeias as taxas de substituição térmica são de mais de 98% e a taxa média está em torno de 35%. No Brasil, a taxa média de substituição térmica é de 9% (ABCP, 2013; Aranda Usón et al., 2013; Lamas et al., 2013; SNIC et al., 2012).

No continente europeu, resíduos animais, resíduos sólidos urbanos, lodos de estações de tratamento de efluentes, pneus e biomassa são utilizados para coprocessamento, enquanto no Brasil, o resíduo mais coprocessado é o pneu. Em menores quantidades, são utilizados ainda alguns resíduos industriais e biomassa (Aranda Usón et al., 2013).

Assim, estima-se que há um grande potencial de desenvolvimento da técnica de coprocessamento no Brasil, no entanto, a falta de dados acerca do tema desfavorece esse avanço (Rocha et al., 2011). Nesse sentido, este estudo, pretende, por meio da técnica de Avaliação do Ciclo de Vida, fazer um diagnóstico ambiental da produção de cimento na Europa e no Brasil e, ao comparar esses cenários, verificar a viabilidade de aplicação da técnica de coprocessamento no Brasil.

A ACV é uma metodologia de gestão ambiental que permite, a partir de dados de entradas e saídas inerentes à serviços, processos e produtos, quantificar seus impactos ambientais (ISO, 2006a, 2006b).

Desta maneira, este estudo espera avaliar, ambientalmente, a produção de cimento no Brasil, em comparação com o cenário Europeu e mundial. A principal motivação deste trabalho é identificar oportunidades de melhoria da qualidade ambiental do cimento produzido no país, por meio da identificação de oportunidades de aprimoramento da técnica de coprocessamento.

1.1. Objetivos

1.1.1. Objetivo Geral

Verificar a viabilidade da aplicação da técnica de coprocessamento no Brasil por meio da avaliação do desempenho ambiental da indústria de cimento nacional e Europeia com base em dados primários e diretrizes de cada região por meio do uso da metodologia de ACV.

1.1.2. Objetivos Específicos

- Avaliar ambientalmente o processo de produção de cimento no Brasil com base em (I) dados primários obtidos de uma empresa produtora de Cimento Portland CP II e CP IV e em (II) dados secundários obtidos com os órgãos competentes.

- Avaliar ambientalmente o processo de produção de cimento na Europa com base em (I) dados primários obtidos de uma empresa produtora de Cimento Portland CP I.

- Comparar os impactos ambientais calculados pela metodologia de ACV em cada região, levando em consideração o desenvolvimento econômico, e sugerir direções para processos mais eficientes e ambientalmente amigáveis.

- Comparar métodos de avaliação de impactos e a influência destes no resultado final de uma ACV.

- Diagnosticar o desempenho ambiental do setor cimenteiro no Brasil e na Europa em relação ao panorama mundial.

1.2. Estrutura da Tese

Este documento é concebido em estrutura de artigos.

O Capítulo 2 é a exposição do tema estudado e apresenta um artigo, ainda em avaliação pelo periódico ao qual foi submetido, referente à uma comparação entre o desenvolvimento da técnica de coprocessamento na América Latina e na Europa, e um artigo já publicado referente aos desafios para o coprocessamento na América Latina. A última seção deste Capítulo discorre sobre a ACV.

O Capítulo 3 refere-se à metodologia geral utilizada neste trabalho. Para a condução deste estudo, foram analisados três cenários, denominados “Empresa Europeia”, “Empresa Brasileira” e “Estimativas Brasil”.

O detalhamento de cada um dos cenários é apresentado no Capítulo 4, Resultados e Discussão, que é apresentado em sua maioria na forma de artigos (todos submetidos a periódicos indexados).

O primeiro artigo trata dos resultados encontrados para o cenário "Empresa Europeia". Esse trabalho, com o intuito de ser comparado a outros trabalhos já desenvolvidos para a região, foi realizado com o método CML 2001. No entanto, o método Recipe é atualmente mais aceito, de modo que nas seções seguintes apresenta-se uma nova análise do mesmo cenário, mas com o método Recipe e, dentro do possível, uma comparação entre os dois métodos.

A próxima seção apresenta o artigo referente ao cenário "Estimativas Brasil", desenvolvido com base em dados gerais da produção de cimento no país e no método Recipe, enquanto a seguinte seção apresenta a análise do cenário "Empresa Brasil", também pelo método Recipe.

Em seguida apresentam-se algumas considerações sobre a geração de energia elétrica associada aos cenários estudados. A última seção deste capítulo apresenta a Normalização dos resultados apresentados para os cenários anteriores segundo o método Recipe.

Finalmente, o Capítulo 5 expõe as conclusões deste estudo e, o Capítulo 6 elenca as sugestões para trabalhos futuros. Devido a esse formato de apresentação, pode haver quebra de continuidade da lógica textual e repetição de informações, que são necessárias a cada artigo, mas dispensáveis na estrutura da tese. Como os artigos já foram publicados ou estão na formatação para o periódico ao qual foram submetidos, pode haver também divergência de formato.

1.3. Originalidade

A atividade de coprocessamento no brasil é pouco explorada cientificamente. Na literatura internacional encontrou-se apenas um artigo, publicado no Renewable and Sustainable Energy Reviews, que trata da economia de energia térmica derivada do uso de pneus nos fornos de cimento (Lamas et al., 2013). Outros estudos foram encontrados na literatura nacional, em sua maioria baseados nos benefícios do uso do coprocessamento de pneus e de biomassa (Costa et al., 2013; M. A. Sellitto et al., 2013). Trabalhos adicionais, que usam a ACV como metodologia, baseiam-se em dados de literatura e não contemplam etapas essenciais da produção como uso de energia elétrica e transportes (Borges et al., 2014). Demais estudos referentes ao coprocessamento, ainda que não realizados com o objetivo de avaliar a produção nacional de cimento, referem-se principalmente aos impactos das emissões de CO2 e, em geral, apresentam muitos problemas em relação ao levantamento de dados (P. Gursel et al., 2014; Josa et al., 2007, 2004). Nesse sentido, são contribuições originais deste trabalho:

- Avaliação do desempenho ambiental da indústria de cimento no Brasil com base em dados de uma planta produtora;
- Avaliação de impactos ambientais até então negligenciados, tais como impactos sobre a terra e a água e impactos de toxicidade;
- Avaliação de oportunidades e perspectivas para tornar o processo de produção de cimento nacional mais ambientalmente amigável.

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2. EXPOSIÇÃO DO TEMA

2.1. O Cimento Portland

Cimento Portland é um material pulverulento, constituído basicamente de silicatos e aluminatos de cálcio, obtidos a partir do clínquer. Esses silicatos e aluminatos, ao serem misturados com água, hidratam-se e produzem o endurecimento da massa, que pode então oferecer elevada resistência mecânica (Petrucci, 1978). É um dos componentes do concreto, material sólido manufaturado mais utilizado no mundo (EPA, 2012).

Os constituintes fundamentais do cimento Portland são a cal (CaO), a sílica (SiO_2) e a alumina (Al_2O_3), cujo diagrama de fases é apresentado na Figura 1. Para uma melhor compreensão desta, a Tabela 1 apresenta as abreviações usuais para expressão dos óxidos individuais e compostos do clínquer.

Tabela 1: Nomenclatura de óxidos e compostos presentes no clínquer.

Óxido	Abreviação	Composto	Abreviação
CaO	C	$3CaO.SiO_2$	C_3S
SiO_2	S	$2CaO.SiO_2$	C_2S
Al_2O_3	A	$3CaO.Al_2O_3$	C_3A
Fe_2O_3	F	$4CaO.\ Al_2O_3.Fe_2O_3$	C_4AF
MgO	M	$4CaO.\ 3Al_2O_3.SO_3$	$C_4A_3\bar{S}$
SO_3	$\bar{S}$	$3CaO.\ 2SiO_2.3H_2O$	$C_3S_2H_3$
H_2O	H	$CaSO_4.\ 2H_2O$	$C\bar{S}H_2$

Adaptado (Mehta and Monteiro, 2014).

Esses componentes, e ainda o óxido de ferro (Fe_2O_3), constituem, geralmente, 95 a 96% do total na análise de óxidos. Além desses componentes, outros são encontrados, como certa proporção de magnésia (MgO), óxidos de sódio e potássio (Na_2O e K_2O, respectivamente) e quantidades menores de outros compostos (Bauer, 2008).

A mistura dessas matérias primas em proporções rigorosamente definidas é submetida à ação de calor, resultado na obtenção do clínquer, ao qual é adicionado uma pequena quantidade de anidrido sulfúrico, SO_3, com o objetivo de retardar o tempo de pega do cimento (Bauer, 2008).

Cada componente confere características e propriedades específicas à mistura, conforme descrito por Petrucci (Petrucci, 1978).

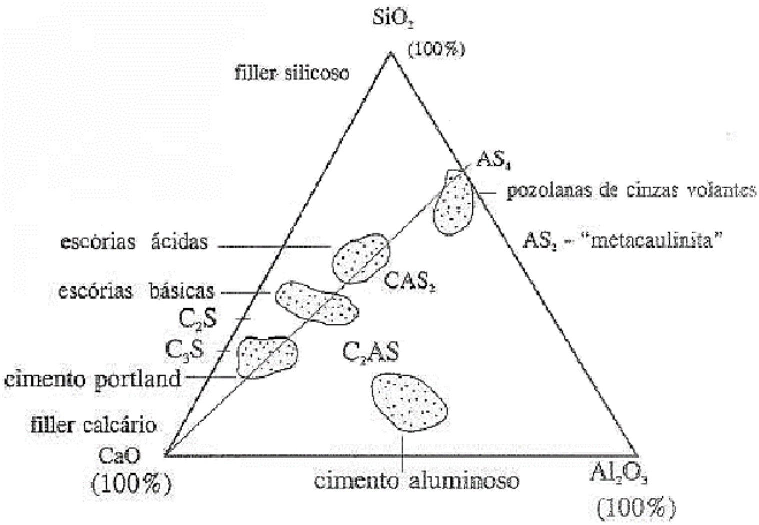

Figura 1: Diagrama ternário do sistema $CaO\text{-}SiO_2\text{-}Al_2O_3$.
Fonte: (Junior, 2012).

- CaO: provém da decomposição do carbonato de cálcio e pode-se dizer que as propriedades mecânicas do cimento Portland aumentam, tanto maior for o teor de cal, desde que se encontre completamente combinada;
- SiO_2: é encontrada combinada com outros componentes e provém das argilas usadas como matéria prima, prima (ou da correção com areia siliciosa). É da sua combinação com a cal que resultam os principais componentes do cimento Portland.
- Al_2O_3: também proveniente das argilas. O composto formado pela sua combinação com a cal acelera a pega do cimento Portland e reduz a sua resistência aos sulfatos.
- Fe_2O_3: exerce função fundente, com ação até mais enérgica do que a alumina nesse sentido.

• MgO: admite-se que no cimento Portland, a magnésia não se encontra combinada. Em quantidades superiores a certos limites (≈1% em massa), atua como agente expansivo, agindo de forma nociva sobre a estabilidade dimensional/volumétrica das argamassas e concretos.

• Na_2O e K_2O: também chamados de álcalis do cimento, agem como fundentes e aceleradores de pega. Os seus teores são também restritos por norma, uma vez que são responsáveis por fenómenos que afetam a durabilidade dos cimentos e concretos (ex. sais solúveis, reações com agregados).

2.2. Produção e Consumo

Estima-se que no ano de 2012 a produção mundial de cimento foi de 3,6 bilhões de toneladas (Cembureau, 2014), e as previsões até 2050, indicam um aumento considerável nesse número (WBCSD, 2009a).

Uma parcela importante desse montante é originada na China, que desde 2011 supera a marca de 2 bilhões de toneladas produzidas por ano (CEMBUREAU, 2012). Devido a fatores como o baixo valor e o caráter perecível do cimento, é preciso considerar também a tendência ao consumo local, próximo às fábricas (SNIC, 2013a).

Por isso pode-se afirmar que a produção está intimamente ligada ao consumo de cimento em determinado país ou região, e que este é fortemente relacionado à situação econômica e estágio de desenvolvimento das nações (CEMBUREAU, 2013). Nesse contexto, Índia, União Europeia, Estados Unidos e Brasil figuram entre os principais produtores de cimento nos últimos anos, ficando atrás apenas da China, conforme demonstrado na Figura 2 (CEMBUREAU, 2012).

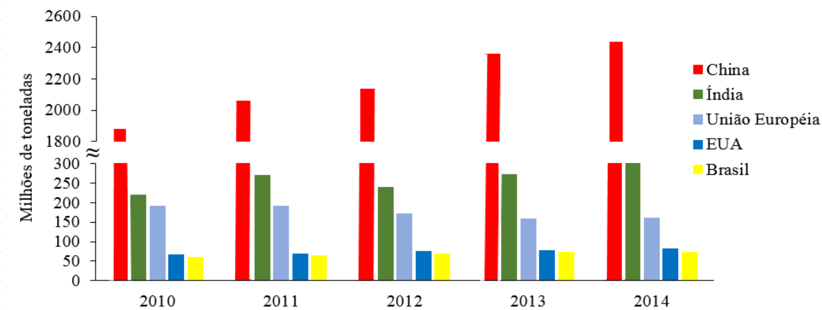

Figura 2: Principais produtores de cimento entre 2010-2014. Adaptado de (Cembureau, 2014).

Além da expressiva produção em nível mundial, a manufatura do cimento tem impactos ambientais que não podem ser negligenciados. A produção de uma tonelada de cimento Portland demanda o consumo de pelo menos 1,4 toneladas de matérias primas, em torno de 110 kWh de energia elétrica e de 60 a 130 kg de combustíveis (Huntzinger and Eatmon, 2009; Lamas et al., 2013). No sentido de minimizar os impactos ambientais decorrentes do largo uso de matéria e energia, muitos esforços vêm sendo realizados no sentido de otimizar o processo produtivo em questão. Uma das soluções já praticadas é o coprocessamento, que consiste na substituição de matérias primas e combustíveis por materiais alternativos, em sua maioria, pneus, resíduos de outras indústrias, resíduos sólidos urbanos e biomassa (Aranda Usón et al., 2013).

2.3. The Co-processing Operation in Latin America and Europe Cement Industries[1]

2.3.1. Introduction

Concrete is the most widely used manmade material and it is composed by water, cement, aggregates and additives. the most well-known form of cement is Portland, which is made of clinker and additives (WBCSD, 2009b). Clinker is produced from natural extracted raw materials such as limestone, clay and marl and smaller amount of other natural minerals, such as sand, bauxite and iron ore. These materials are mixed, originating the raw mix, which is fed to a kiln for pyro-processing at about 1450°C. After a cooling process, the clinker is conveyed to a ball mill for final grinding. in the final mill system, clinker is mixed with a small amount of gypsum in order to finally obtaining Portland cement (Strazza et al., 2011). According to CEMBUREAU, the cement production in 2012 was around 3.6 billion of tonnes and the world business council for sustainable development (WBCSD) stated that the cement production is projected to grow 0.8 to 1.2% per year until 2050 (WBCSD, 2009a). Moreover, the production of

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http://www.crcnetbase.com/doi/abs/10.1201/b18853-56

cement involves the consumption of large quantities of energy, obtained from a number of different sources (Valderrama et al., 2012). Obviously, the huge amount of energy consumed in the cement production has impacts on the environment. Main emissions are carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x) that occur during the pyro-processing. They are mostly related to the chemical reactions and usage of fossil fuels and are responsible for impacts as climate change, acidification and eutrophication, respectively. in fact, 60% of the emission of CO_2 is due to the limestone decarbonatation, but other 40% is related to the use of fossil fuels (Pacheco-Torgal et al., 2014).

In this scenario, the use of wastes as an alternative to replace raw materials and fossil fuels is a valid option that provides a solution in terms of reducing fossil fuel dependency as well as is a contribution to achieve lower emissions. this replacement is called co-processing and if carried out in a safe and sound manner it should not affect health and safety of workers or neighborhood (Cembureau, 2009).

Thus, in this work we analyse the status of co-processing operations in European and Latin American countries. In the first section, co-processing in Europe is discussed as a regular practice. In the following section, we present the efforts made to achieve adequate ways of carrying out co-processing in Latin America. Finally, we made considerations regarding similarities and differences in these two studied scenarios.

2.3.2. Co-processing Operation

According to the Cement Sustainability Initiative (CSI), there is substantial evidence that cement manufactured from different types of waste does not change significantly the characteristics of the cement or concrete. However, high levels of some minor components can affect cement performance and it is necessary to assure that specific thresholds are not exceeded (Fonta, 2013). Figure 3 presents a production line of

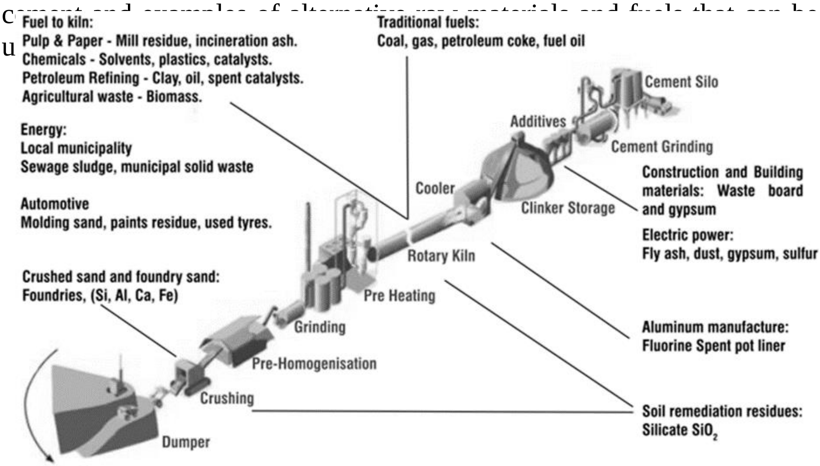

Figure 3: Production line of cement and examples of alternative raw materials and fuels that can be used (Fonta, 2013).

The decision on what type of waste can be used in a certain plant cannot be answered uniformly. As a basic rule, a waste accepted as an alternative fuel and/or raw material must give an added value for the cement kiln in terms of the calorific value of the organic part and the material value of the mineral part. However, several factors must be taken into consideration when deciding on the suitability of the materials, including cement chemical composition as well as the environmental impact of the production process. Nuclear waste, infectious medical waste, entire batteries and untreated mixed municipal waste are examples of residues which are not suitable for co-processing in the cement industry (CEMBUREAU, 2009). Some technical criteria have been established for using wastes as raw materials and fossil fuels, such as their physical state, calorific value, physical and grinding properties, moisture content (water content below 20%), compatibility with the current technology or accessible technical changes. Moreover, the cement quality must not be affected and alternative fuels cost must be lower than traditional fuels (Aranda Usón et al., 2013).

2.3.3. Co-processing in Europe

Several cement producers are present in European Union, totalizing more than 260 cement plants. European business groups members of CSI are CRH (Ireland), Heidelberg Cement (Germany), Holcim (Switzerland), Italcementi Group (Italy), Lafarge (France), and Secil (Portugal). CEMEX (Mexico) and Votorantim (Brazil) are also CSI members (Aranda Usón et al., 2013; CSI, 2014). According to WBCSD, countries of the European Union produce around 250 megatonnes of cement per year, and this number tends to stabilize (WBCSD, 2009a). The fuels used in cement kilns are fossil fuels as petroleum coke and coal and, since the 70’s, alternative fuels started to be used as well (Lamas et al., 2013). Nowadays, they include animal meat and bone meat, municipal solid waste (also called refuse derived fuel, RDF), sewage sludge, biomass and end-of-life tyres (Aranda Usón et al., 2013). Typically, in European countries, the average substitution rate is over 50% for the cement industry and up to 98% as yearly average for single cement plants. In 2010-2011, the replacement ratio reached 83% in the Nertherlands, 62% in Germany and 60% in Norway, but in the same period, other countries did not reach a replacement ratio of 10% (Aranda Usón et al., 2013).

A successful example is the case of Belgium. In 1999, an urgent solution was needed for the treatment of thousands of animal meal and fat from potentially contaminated animal products. The federal authorities identified the co-processing of the contaminated meat and bone meal in the cement industry as the best way of resolving this crisis. Belgian plants were requested to treat a large amount of animal meal, allowing the complete destruction of the potential contaminants in the kiln, as well as reducing emissions as a result of fossil fuel substitution (CEMBUREAU, 2009).

It seems to be consistent with the general statement that Nordic countries and the Netherlands have, in general, a much higher use of alternative fuels due to more advanced and efficient waste recycling schemes in place (Josa et al., 2004). Besides this, many companies are working on reduce the CO2 emissions replacing fossil fuels by alternative fuels. Among the main European cement producers some numbers and initiatives must be highlighted: the Irish industry CRH used 430,000 tonnes of alternative wastes in 2013, which express alternative fuels as 21.2% of the fuel mix. In that year, 54% of alternative fuels were solid recovered fuels and 23% were biomass (CRH, 2013). The German Heidelberg Cement has as aim for 2020 the leadership in the co-processing of alternative fuels and raw materials using the potential of hazardous waste, sorted municipal solid waste and sewage sludge in combination with local opportunities (Heidelberg Cement, 2011). In 2014, the French Lafarge has used 20.7% of alternative fuels instead of fossil fuel, of which 38% was biomass. The goal to 2020 is using 50% of alternative fuels, of which 30% should be biomass (Lafarge, 2014). Another interesting initiative is the mobile sorting lines offered by the Swiss Holcim to companies that collect municipal waste, providing flexibility and extends the waste preprocessing service. In 2014, 14% of Holcim’s thermal energy demand was covered by co-processing alternative fuels. By 2030, the company aspire to use 1 billion tons of secondary resources, replacing approximately 25% of primary materials(Holcim, 2015a). Indeed, Holcim also stands out for its initiative Geocycle, which is now, a network of 38 companies developing innovative industrial and municipal waste management services for a wide range of customers, aiming a zero-waste future (Geocycle, 2015).

In general, the companies have established programs and targets to replace fossil fuels, by investing in modernization of facilities and programs for waste management. This enabled an increase in replacement rates and reducing operating costs, reasons why these actions are now being extended throughout the world. However, facilities using alternative fuels still continue to generate concern, particularly in the surrounding residential areas. It is especially intense when the facilities are located near populated areas (Rovira et al., 2014), which can originate cases of NIMBY (not in my backyard) syndrome. The NIMBY syndrome reflects is an opposition to local siting of hazardous waste facilities and other locally unwanted land uses. Thus, no matter how technically suitable a proposed facility is, there is the possibility that its siting may be obstructed by a NIMBY movement

(Kikuchi and Gerardo, 2009). In a characteristic case, a co-processing of hazardous waste was established by the Portuguese government in 2000 as a “National Strategic Plan of Waste Management”. Since then a number of discussions regarding health and safety and further legal requirements are happening. Only in 2008, after a number of tests, the first co-processing operation has started. However, since then, it has been subject to legal decisions that sometimes allow the operation and sometimes suspend it (A. P. do Ambiente, n.d.; CIMPOR, n.d.; Publico.pt/ciencia, n.d.).

2.3.4. Co-processing in Latin America

The annual cement production in Latin America is estimated in 200 megatons of cement per year and projected to grow to 400 megatons in 2050 (WBCSD, 2009a). The biggest cement producers in Latin America are Brazil, Mexico and Argentina. According to CEMBUREAU, those Latin American countries integrate the list of the 20 biggest producers of cement in the world (CEMBUREAU, 2012). Additionally, according to the Federación Interamericana del Cemento (FICEM), Colombia is another important producer, which reached in 2012 an equivalent cement production than that of Argentina (FICEM, 2012). Besides this, the market is composed in part by small producers and in part by some of the major world business groups, as the Swiss Holcim and the French Lafarge, and others locally originated as the Mexican Cemex and the Brazilian Intercement and Votorantim (Holcim, 2015b; InterCement, 2015; Lafarge, 2015; Votorantim, 2015; “Worldwide Locations|Cemex,” 2013).

Data from the International Cement Review, indicates that Latin America have 224 cement factories, of which more than 60% are local producers (“International Cement Review,” n.d.). The use of co-processing operations started in the 90’s and the most common wastes used nowadays to replace fossil fuels are tires, plastics, textiles, sawdust and wood, wastes from the production of paper, and others such as spent oils or solvents and inks. There is also a promising field to the use of biomass, especially rice husk, peanut and sunflower bagasse.

The substitution rates in Argentina, Brazil, Chile, Costa Rica, Colombia, Guatemala, Mexico and Dominican Republic vary between 7 and 18% (FICEM, n.d.). In this scenario, for promoting the responsible co-processing in these and other countries, FICEM instituted a working group on climate change and co-processing with the participation of industry experts from different associated countries. The intent was preparing the Latin American industry to further regulations concerning climate change and supports the development of local regulations to co-processing (FICEM, n.d.).

In addition, according to the Intergovernmental Panel on Climate Change (IPCC), many industrial facilities in developing nations are new and include the latest technology with the lowest specific energy use. However, many older, inefficient facilities remain in both industrialized and developing countries so there continues to be a huge demand for technology transfer to upgrade industrial facilities to improve energy efficiency and reduce emissions (IPCC, 2007).

An interesting case in Latin America occurs in Brazil. Currently, 1.3 megatons per year of waste are co-processed in Brazil's cement industry, representing about 8% of the fuel matrix; however, the sector has potential to dispose around 2.5 megatons per year, offering potential for additional CO_2 emission reductions (Kihara and Visedo, 2014). In this context, the Brazilians Votorantim and Intercement occupy a prominent position: Votorantim has more than 90% of facilities authorized to co-processing, while Intercement reached 37% rate of thermal substitution in Candiota facility in 2012. In the same year, these two companies coprocessed more than 500,000 tonnes of wastes, each one.

The Mexican CEMEX states that they "put in place corporate guidelines for the introduction and handling of alternative fuels and raw materials in cement kilns to complement local regulation or to serve as a substitute where no regulation exists". However, the most intense use of alternative fuels take place in European facilities through the use of Climafuel® refuse derived fuel (United Kingdom) and Enerfuel (Spain) ("Alternative fuels and renewable energy|Carbon Strategy|Cases Studies|CEMEX," 2013).

2.3.5. Comparing Scenarios

Opposite to the developed economies of Europe, Latin America is basically constituted by developing economies that are facing many challenges regarding political, social and environmental concerns. Certain countries have standards, regulations and laws for waste management and co-processing, which basically prohibit using untreated urban waste, radioactive, organochlorine, hospital and health services residues, pesticides and other related wastes (FICEM, 2012). Thus, the lack of regulations and properly waste management strategies constitute an obstacle to promoting co-processing. A great potential to encourage the practice comes from the amount of viable waste generated every year and the main cement producers: the presence of multinational companies in Latin America has been promoting the use of wastes as fuels. However, Cemex recognizes that the use of alternative fuels is highest in Europe. For example, in 2009 they reached substitution taxes of 26% in Spain. The taxes were even better in United Kingdom (40%) and Germany (48%), but the Mexican taxes for the same year were 8% (“Alternative fuels and renewable energy|Carbon Strategy|Cases Studies|CEMEX,” 2013; CEMEX, 2013a).

2.3.6. Conclusions

Co-processing operations have been developed in Europe since the 70's. These almost fifty years of experience can teach important lessons of using co-processing as an alternative to landfilling, the role of properly waste management and last, but equally important, the popular participation in the project and installation of an unit that co-processes hazardous wastes. In Latin America, a number of efforts have been made as an attempt of achieve better levels of use of wastes in cement industries. In addition, the presence of multinational companies, such as CEMEX, Holcim and Votorantim has been promoting the use of wastes as fuels. Many countries are celebrating agreements and developing strategies and regulations to improve waste management and stimulate the co-processing, such as the working group started by FICEM in 2010. Despite many problems, a few associated to the incorrectly destination of wastes, Latin America has potential to increase co-processing due the amount of waste generated every year and its cement production.

2.4. Advances and Challenges for the Co-processing in Latin American Cement Industry[2]

[2] Presented at SAM – CONAMET 2014, Santa Fe, Argentina.
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http://www.sciencedirect.com/science/article/pii/S2211812815002163

2.4.1. Introduction

Cement is the main component of concrete, which is the most consumed material on Earth(WBCSD, 2009b). Its production reached 3.6 billion of tonnes in 2012 and it is projected to grow by 0.8-1.2% per year until 2050 (CEMBUREAU, 2012; WBCSD, 2009a). Besides the amount consumed every year, the production of cement involves heating a mix of limestone, clay and bauxite, at temperatures between 1200°C and 1500°C (Lamas et al., 2013). This process provides the decomposition of calcium carbonate into calcium oxide, which causes high CO2 emissions. In addition, huge quantity of electricity is required to grinding the raw materials and the finished cement (Edenhofer et al., 2012). This high energy consumption and the decarbonatation of limestone make the cement industry responsible for approximately 12 to 15% of total industrial energy use (Madlool et al., 2011) and 5 to 7% of the anthropogenic CO2 emission (Fry, 2013a).

Actually, each ton of Portland cement produced releases almost one ton of carbon dioxide to the atmosphere (Meyer, 2009). Due to this, a significant effort has been made in terms of researches and new methods developing to reach lower CO2 emissions (CEMBUREAU, 2009; FICEM, 2012; Madlool et al., 2011; Meyer, 2009).

An already well known and broadly used method is the co-processing, technique in which waste is used to replace raw materials and/or fuels (CEMBUREAU, 2009). According to the European Cement Association, CEMBUREAU, the co-processing of alternative fuels provides a solution in terms of reducing fossil fuel dependency as well as a contribution towards the lowering of atmospheric emissions.

The use of alternative raw materials also has numerous benefits, including a reduced need for quarrying and an improved environmental footprint of such activities. Besides this, those substitutions do not have negative impacts on production process emissions, or on the environmental and technical quality of the final product. Furthermore, co-processing is carried out in a safe manner, thus not affecting the health and safety of its workers or neighborhood (CEMBUREAU, 2009).

According to Usón (Aranda Usón et al., 2013), the common wastes used worldwide in cement industries are municipal solid waste, meat and bone animal meal, sewage sludge, biomass and end of life tires, but the case of the Netherlands is remarkable. This country reached a replacement ratio of 83%, and approximately 42% comes from sewage sludge. Other industrialized countries show replacement ratios above 60%, as Austria, Germany and Norway. In 2010, the average for the UE-27 was 30.5%. Despite these excellent numbers, it is important to give attention to developing economies, because it is estimated that they are responsible for 80% of global cement production (WBCSD, 2009c). In Latin America, the main producers are Brazil, Mexico and Argentina. In 2012 they figured among the 20 main cement producers in the world, occupying the 5th, 12th and 18th position, respectively (CEMBUREAU, 2012).

The Intergovernmental Panel on Climate Change (IPCC) says that many industrial facilities in developing nations are new and include the latest technology with the lowest specific energy use. However, many older, inefficient facilities remain in both industrialized and developing countries. Also, in developing countries, there continues to be a huge demand for technology transfer to upgrade industrial facilities to improve energy efficiency and reduce emissions (IPCC, 2007).

Thus, the central questions in this paper are the cement production in Latin America, the current situation of co-processing and the challenges to reach a more sustainable cement industry. First, we give a brief overview of the cement industry in Latin America, and then we discuss the status of co-processing for the most expressive cement industries.

In addition, we discuss the legal requirements concerning the activity and how the waste management chain can enhance the progress in terms of sustainability. Some countries are not discussed due the lack of reliable information. Finally, we analyze the waste management chain, legal requirements and how they can enhance the progress in terms of sustainability.

2.4.2. Cement Industry in Latin America

The biggest cement producers in Latin America are Brazil, Mexico and Argentina. According to CEMBUREAU, they are the Latin American countries that integrate the list of the 20 biggest producers of cement in the world. Together they were responsible for the production of 120 million of tonnes of cement in 2012 (CEMBUREAU, 2012). Additionally, according to the Federación Interamericana del Cemento, FICEM, Colombia is another important producer, that, in 2012, reached the same quantity of Argentina cement production (FICEM, 2013). Table 2 summarizes the cement production between 2010 and 2012 in Latin America for the countries that produced more than 5 millions of tonnes in 2012.

Table 2: Cement production between 2010 and 2012 for the biggest producers of Latin America.

Country	**Cement production (millions of tonnes)**		
	2010	**2011**	**2012**
Brazil	59.2	64.1	68.8
Mexico	34.5	35.4	36.8
Colombia	9.5	10.8	10.9
Argentina	10.4	11.6	10.7
Peru	8.3	8.5	9.8
Venezuela	7.1	7.7	8.3
Ecuador	5.3	5.7	6.0
Chile	4.4	4.6	5.0

Adapted from Informe Estadístico 2013 (FICEM, 2013).

The Brazilian market is composed of many producers and have an installed capacity of cement production of 78 millions of tonnes per year(SNIC, 2013a). However, the major Latin American cement company is the Mexican CEMEX, which has only in Mexico 15 factories, responsible for an installed capacity of 29.3 millions of tonnes of cement per year(Sobrinho et al., 2012). CEMEX also has a number of others factories around the world, which totalize an installed capacity of production of 93.7 millions of tonnes(CEMEX, 2013). Other main producers at Mexico are Holcim, Lafarge and Cementos Moctezuma (CANACEM, 2014). In the same way, Argentina also has many players in the cement market, but the main producers are Loma Negra (trademark of the Brazilian group Camargo Correa, administered by the holding Intercement) and the Swiss Holcim. The others are local producers and together they correspond to almost half of the installed capacity (Cimento.org, 2014), that totalize 16.8 millions of tons. Contrary to these, there is Colombia, which is considered an oligarchic market. In 2005, the sector faced accusations of collusion (a non-competitive agreement between companies to disrupt the market's equilibrium). Due to this crisis, smaller producers were forced to close or were absorbed by larger groups. Nowadays, only 3 companies act at Colombian market: Argos, Cemex and Holcim (Aktiva Servicios

Financieros, 2013). Besides the Colombian case, there are other markets dominated for few players, like Bolivia, Venezuela and all small countries from Central America. Data from the International Cement Review, indicates that Latin America has 224 cement factories, of which more than 60% are local producers. In Table 3 we present the producers that complete the Latin America cement framework and also act in other countries worldwide.

Table 3: Latin America main industrial groups.

Group	**Origin**	**Locations worldwide**
Argos	Colombia	Colombia and USA
Cemex	Mexico	Argentina, Colombia, Costa Rica, Dominican Republic, El Salvador, Mexico, Nicaragua, Panama, Peru and Phillipines, USA and factories in Asia and Europe
Holcim	Switzerland	Chile, Argentina, Brazil, Colombia, Ecuador, Costa Rica, Nicaragua, El Salvador, Mexico, Canada, USA and factories worldwide
Intercement	Brazil	Argentina, Paraguay and Brazil and factories in Africa and Portugal
Lafarge	France	Brazil and Ecuador, Canada, USA and factories in Africa, Asia and Europe
Votorantim	Brazil	Argentina, Bolivia, Brazil, Colombia, Peru, Canada, USA, and factories in Africa, Asia and Europe

Based on (Argos, 2012; HOLCIM, 2013; Intercement, 2012; Lafarge, 2014; Votorantim, 2014).

2.4.3. Co-processing in Latin America

From the companies mentioned in Table 2, Cemex has an outstanding position in terms of co-processing. For two consecutive years they have been recognized with a Global Cemfuels Award for Alternative Fuels Using Company of the Year (CEMEX, 2013b). Despite this, Cemex recognizes that the use of alternative fuels is highest in Europe. For example, in 2009 they reached substitution taxes of 26% at Spain. The taxes were even better at United Kingdom (40%)

and Germany (48%), but the Mexican taxes for the same year were 8% (CEMEX, 2009). The company attributes this to local regulations of waste management. According to Cemex "in many countries, our alternative fuels substitution rate is low, far below its real potential. The reason is that our technical know-how must be matched by appropriate waste management regulations" (CEMEX, 2013a). For Argos, the current situation is the same. Two plants in USA present substitution rates of 15% and 23%, while plants in Colombia still are being prepared to begin co-processing in a plan of three years (2013-2015) (Argos, 2012). Holcim has kept its global substitution rates around 12% between 2010-2012 (HOLCIM, 2013), and it is important to highlight that the company has been responsible for developing and improving co-processing in many countries. In 2003, Holcim and the German Gesellschaft für Technische Zusammenarbeit (GTZ) started a partnership agreement that led to the development of guidelines for the utilization of waste materials in the cement industry. These guidelines are particularly designed to improve waste management in developing countries. At the end of 2005 the partners entered into a second three-year lasting co-operation to advance the implementation of the guidelines which was successful in more than 20 countries until now (HOLCIM, 2014). Intercement closed 2012 with 9% substitution rate. The goal is to reach 32% until 2017. The strategy includes (1) investments in knowledge; (2) adequacy the structure to receive, store and destroy the wastes; and (3) sharing success experiences among company facilities. Here, they highlight the Candiota facility, in Brazil, that reached 37% substitution rate in 2012(Intercement, 2012). Besides this, in 2005, Cimpor (which is an Intercement business) created together with Lafarge a joint venture specialized in waste management and co-processing: the Ecoprocessa. Its main objective is foster co-processing in the 11 factories of the companies. In 2013, Lafarge's global substitution rate was 10%, but in Brazil, the number was almost 13%. Additionally, the Lafarge Cantagalo facility was the pioneer in co-processing urban waste from the selective collect. In this scenario, the Brazilian company Votorantim also plays an important role. The company practices co-processing since early 90s and more than 90% of the facilities are authorized to receive wastes to co-processing (Votorantim, 2014).

It is also important to say these six companies are members of the "Cement Sustainability Initiative", which is a sector-project of the

World Business Council for Sustainable Development. There are another 18 industries spread worldwide participating of this project, which is a global effort for the pursuit of sustainable development in the cement industry (CSI, 2014). The presence of these companies in Latin America and its participation in a global project like CSI cooperates for the development and implementation of co-processing in countries whose waste management provided by the local governments is weak or ineffective.

2.4.4. Waste Management and Legal Requirements

International companies, whose market share is increasing, usually adopt their own internal standards throughout the world, using best available technologies when building new facilities. Actually, from a technical point of view, all kiln types are suited for co-processing, however, older, polluting, and less integrated technologies are gradually being phased out due to stricter standards and/or voluntary best practices (GTZ-Holcim, 2006). Countries as Brazil, Colombia, Costa Rica, Mexico and others have standards, regulations and laws for co-processing and waste management. Obviously, these regulations vary according to each country, but basically, they prohibit using untreated urban waste, hospital waste and from health services, radioactive, organochlorine, pesticides and others related (FICEM, 2012).

Besides the environmental dimensions of the co-processing, it is necessary to take into account the social dimensions of this practice. The technique can create risks to the health of workers and surrounding population if it is not properly used. Additionally, health and safety have been the major concerns in hazardous waste management. Therefore, modern waste management should include (i) technical efficiency in terms of environmental protection, (ii) economic efficiency in terms of cost feasibility, and (iii) social acceptability (Kikuchi and Gerardo, 2009). Thus, the rules concerning to what wastes can be employed and the limits of atmospheric emission of pollutants should be well defined and strictly met and inspected.

In this way, many efforts have been made in Latin America. In Brazil, for instance, there is a law specifically about co-processing since 1999, but the lack of infrastructure for waste management, hinders its practice. In fact, in 2007, 800.000 tonnes of industrial wastes were co-processed in the country, but it corresponds only to 30% of all industrial wastes produced that year. The main kind of wastes used are contaminated soil, tires, oily sludge, used catalysts, adhesives, resins, latex, rubberized and contaminated materials as paper plastics and woods (Bauer, 2008).

In Costa Rica, a properly regulation about co-processing was developed in 2004 due to the Holcim Costa Rica S.A. interest in co-processing industrial wastes. Before this, industrial waste was collected from private companies and co-disposed at environmentally sound handling and disposal of waste material in their cement kilns. Thenceforth, in a joint effort between the cement manufacturers and the Ministry of Health, a regulation that permits the co-processing of used solvents (halogen free), waste oil, waste tires and rubber scrap and plastics (except PVC) was implemented (GTZ-Holcim, 2006).

But while Latin American countries are developing laws and strategies regarding industrial waste co-processing, many European countries are co-processing not only industrial wastes, but also municipal wastes (Usón et al., 2013). Considering the amount of municipal wastes generated every day and the disposal problems in developing countries, co-processing is a good way to run out these wastes. The main issue is that from an ecological, technical and financial point of view, the co-processing of unsorted municipal waste is not recommended. Mixed municipal waste must be sorted in order to obtain defined waste streams of a known quality. Due to this, co-processing municipal waste should be regarded as an integrated part of municipal solid waste management (GTZ-Holcim, 2006). Pioneer in this field in Latin America, Cemex co-process the inorganic materials from urban solid waste (FIRSU®) since 2012. Paper, plastics and textiles that cannot be recycled are sorted, shredded and then used as an alternative fuel in Cemex's cement kilns. In 2013, 84.000 tonnes of FIRSU® were co-processed in 8 cement plants and they aim to roll out the system to the other seven Mexican cement plants by 2016 (Louise Fordham, 2014). Besides this enhancement by private sector, also the Camara Nacional del Cemento (CANACEM) has signed individual accords to the Secretaría del Medio Ambiente y Recursos Naturales de México, and to Petróleos Mexicanos in respect to using wastes from the petroleum industry in the cement production (CANACEM, 2014).

As regional actions, FICEM created a working group focused on climate change and co-processing in 2010. The group is composed by experts from all the associated countries and has as goal preparing the

Latin American cement industry for future regulatory frameworks on climate change, foster co-processing and support the development of legislation that encourages responsible co-processing(FICEM, 2012). Another interesting initiative is the Guidelines on Co-processing Waste Materials in Cement Production, from GTZ-Holcim Public Private Partnership. As known, Holcim holds majority and minority interests in many countries in Latin America (Table 2) and this kind of effort stimulates co-processing practice in the region.

These Guidelines are based on an approach that aims specifically to reduce existing waste problems in developing countries and encourage the use of waste as an alternative source for primary energy and virgin raw materials in cement kilns (GTZ-Holcim, 2006). It is expected that these actions can stimulate the resolution of some waste management problems in developing countries. The main issue is creation and execution of integrated strategies for waste management, and obviously, for this, is necessary to implement and execute laws regarding waste issues and co-processing. Uncontrolled waste disposal still is the cheapest way to run out the wastes, but it is not safe for the environment or human health. The alternative of co-processing brings environmental and social benefits, avoiding the consumption of fossil fuels and giving a properly destination for municipal or hazardous wastes. For this reasons, co-processing is a win-win relation and must be encouraged and enhanced.

2.4.5. Conclusions

The high-energy consumption by cement industries has been a central issue in respect to environmental questions as fossil fuel consumption and climate change. Due to this, co-processing is a win-win alternative, avoiding fossil fuel consumption and at the same time providing an adequate destiny to many kinds of wastes. It is known that co-processing best practices happen in European countries. It happens due to a well-defined regulation and the good waste management, with roles from society, companies and government well defined. However, the presence in Latin America of multinational companies, as CEMEX and Holcim, has been promoting the use of wastes as fuels. In many countries, governments and industry are reaching agreements and developing strategies and regulations to improve waste management and stimulate the co-processing, similar to what happens in Europe. Despite many problems, mostly associated to the incorrectly destination of wastes, Latin America has potential to increase co-processing due the amount of waste generated every year and its cement production.

2.5. Avaliação do Ciclo de Vida

Esta seção discorre sobre a metodologia de avaliação do ciclo de vida (ACV), metodologia chave na condução desse estudo. Conforme explicado a seguir, a ACV compreende quatro fases, sendo que a primeira delas é a definição de objetivo e escopo do estudo e a segunda, a fase de análise de inventário. Como já essas etapas preliminares são diferentes para cada cenário de produção de cimento estudado, estas foram tratadas como parte dos resultados, motivo pelo qual estão detalhadas na seção 4 – Resultados.

Os materiais de engenharia têm um ciclo de vida. A partir das matérias primas, eles são transformados em produtos que são distribuídos e utilizados. No entanto, esses materiais apresentam tempo de vida finito, e frequentemente, tornam-se resíduo quando atingem essa etapa final. Apesar disso, muitos dos materiais que constituem esses produtos podem ser reaproveitados para integrar uma nova cadeia produtiva, sendo utilizados como material reciclado em um novo produto. A ACV traça essa progressão, documentando quais recursos são consumidos e quais emissões são geradas durante cada fase de vida do material. O resultado é um documento que relata lugares por onde o material passou, que transformações sofreu e as consequências associadas a isto (Ashby, 2009).

A Figura 4 mostra cada etapa do ciclo de vida de um de um produto e as entradas e saídas relativas a cada uma. Cada um desses processos pode ser visto como um subsistema do sistema de produto geral (Drive, 2006).

A ACV pode ser definida como uma técnica de gestão ambiental que consiste na compilação e avaliação das entradas, saídas, e dos impactos ambientais potenciais de um produto ou serviço ao longo do seu ciclo de vida, ou seja, desde a aquisição da matéria prima ou de sua geração a partir de recursos naturais, até a disposição final. Assim, ela deve abranger os fluxos de energia e de material durante a aquisição das matérias primas, processamento do produto, distribuição e armazenamento, uso, manutenção e reparos, opções de reciclagem e destinação final.

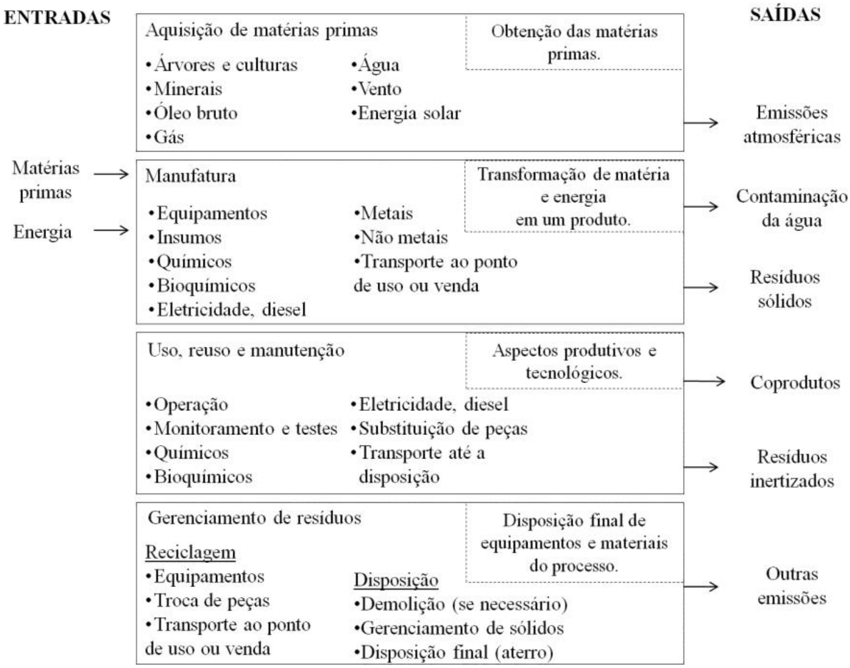

Figura 4: Subsistemas de uma ACV (Drive, 2006).

Não existe um único método para conduzir esse tipo de estudo, então deve haver flexibilidade para implementar a avaliação com base na aplicação específica e nos requisitos específicos do sistema. Apesar disso, algumas condições são estabelecidas, por exemplo, o estudo do ciclo de vida de um material deve ser descrito em um documento que enumere:

- o objetivo e escopo do trabalho;
- a análise de inventário;
- a avaliação de impactos;
- a interpretação dos resultados.

A relação entre essas etapas é demonstrada na Figura 5. Cada uma dessas fases deve ser muito bem compreendida para que o estudo seja desenvolvido com a exatidão e a seriedade necessárias no que tange a questão ambiental.

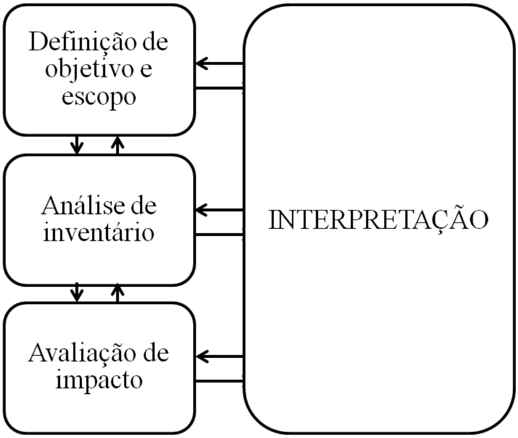

Figura 5: Fases de uma ACV e suas ligações (ISO, 2006a).

2.5.1 Definição do escopo e objetivo

Esses itens devem responder às duas questões que devem direcionar qualquer tipo de pesquisa, que são: “Por que conduzir este estudo?”, e “Onde o estudo deverá começar e terminar?”. Existem diversas razões para se conduzir um estudo de ACV. Pode-se citar, por exemplo, avaliar a necessidade do aperfeiçoamento de um processo produtivo ou um produto, a viabilidade de um novo material, o embasamento de um planejamento estratégico, e até mesmo, a elaboração de políticas públicas.

O objetivo de um estudo da ACV deve declarar inequivocamente a aplicação pretendida, as razões para conduzir o estudo, o público-alvo, isto é, para quem se pretende comunicar os resultados do estudo e se existe a intenção de utilizar os resultados em afirmações comparativas a serem divulgadas publicamente.

Contudo, definir a extensão do estudo de ACV, por mais que a razão de seu desenvolvimento seja conhecida e aceita, pode ser uma tarefa bastante complexa. Dependendo da razão pela qual o estudo será conduzido, nem todas as etapas associadas a um processo ou envolvidas na produção de um material deverão ser consideradas.

Utilizando um material qualquer como exemplo, pode-se entender que existem várias etapas que podem ser observadas para condução de um ACV.

A extração de recursos naturais e seus impactos, a produção do bem material, seu uso ou consumo e sua disposição final podem ser avaliadas individualmente ou em conjunto. Assim, a dimensão do estudo depende da razão pela qual ele está sendo desenvolvido. A Figura 6 ilustra as fronteiras dentro das quais se pode desenvolver um ACV e os fluxos de recursos e emissões que as atravessam (Ashby, 2009).

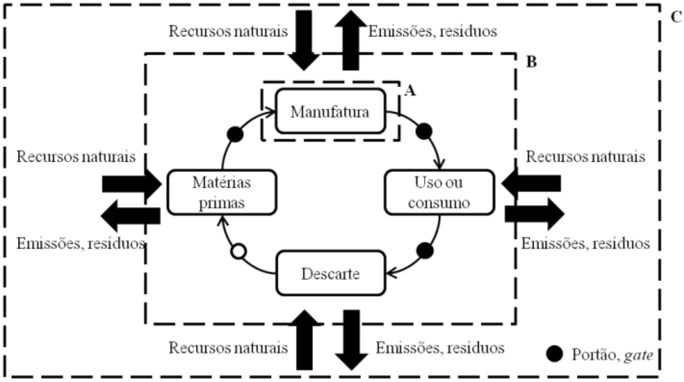

Figura 6: Possíveis fronteiras de um ACV e os fluxos de matéria e emissões através delas. Adaptado (Ashby, 2009).

Com base na Figura 6, verifica-se que o objetivo pode ser:

a) Examinar apenas uma das etapas compreendidas entre “portões”. Pode se referir à produção ou ao uso e consumo do material, ou a essas duas etapas em conjunto, o que corresponde à fronteira A da Figura 6. Neste caso o estudo é conhecido como “de portão a portão” (do inglês gate-to-gate). É muito comum em empresas, onde o processo produtivo é avaliado com o intuito de torna-lo mais sustentável ou econômico.

b) Observar desde a etapa de extração das matérias primas até a manufatura. Também chamado de “do berço ao portão” (do inglês cradle-to-gate). Está relacionado à fronteira B na Figura 6. Também é comum em empresas, no entanto, requer mais tempo e tem maior custo, portanto, nem sempre é viável.

c) Estudar o ciclo completo do material. Este tipo de estudo também é chamado de “do berço ao túmulo” (do inglês cradle-to-grave). Corresponde à fronteira C da Figura 6. É necessário ter algum bom senso na condução desse estudo, uma vez que ampliar demais as fronteiras pode fazer com que a conclusão principal se perca entre a enormidade de dados que serão obtidos. Além disso, despenderá de recursos humanos, econômicos e tecnológicos de diversos setores.

d) Analisar processos de reciclagem associados a um produto. Este último caso leva em consideração a transformação do que seria um resíduo em uma nova matéria prima. É conhecido como “do berço ao berço” (do inglês *cradle-to-cradle*) e representado pela ausência de “portão” entre a etapa de Descarte e Matérias Primas na Figura 6. Com o crescimento das políticas ambientais, deve ganhar espaço no sentido de indicar alternativas de reciclagem que sejam mais interessantes dos pontos de vista ambiental e econômico.

Diante disso, fica clara a necessidade de definir um objetivo claro para a condução do estudo, e ainda, planejar suas etapas o máximo possível, pois dada a grandiosidade e complexidade da sua realização, pode ser fácil incorrer em erros que levem à conclusões equivocadas. Nesse sentido, a elaboração do escopo do estudo é de máxima importância.

Nessa etapa devem ser considerados e claramente descritos: as funções do sistema de produto (ou sistemas, se for um estudo comparativo), a unidade funcional, os fluxos de referência, as fronteiras do sistema, os requisitos de qualidade dos dados, as comparações entre sistemas e as considerações sobre o tipo de análise crítica a ser desenvolvida (se aplicável) (Standard, 2006a).

Um sistema de produto refere-se a um conjunto de processos elementares, com fluxos elementares e de produto, desempenhando uma ou mais funções definidas e que modela o ciclo de vida de um produto. No escopo deve ser claramente especificado as funções do sistema em estudo e uma unidade funcional, que é uma medida do desempenho do que sai do sistema.

As fronteiras do sistema de produto definem onde o estudo começa e onde ele termina, desde que seja satisfeita a aplicação pretendida do estudo. Os critérios utilizados para estabelecer essas fronteiras devem ser identificados e justificados.

Ainda é conveniente que o sistema seja modelado de forma que as entradas e saídas em suas fronteiras sejam fluxos elementares. Nesse sentido, deve ser levado em consideração também as características gerais dos dados necessários ao estudo: período de tempo, área geográfica, tecnologias, precisão, completeza, representatividade dos dados, consistência e reprodutibilidade dos métodos utilizados ao longo da ACV, fonte dos dados e sua representatividade, bem como incertezas das informações.

Essas informações são muito importantes, pois em estudos comparativos, a equivalência dos sistemas que são comparados deve ser avaliada. Assim, esses estudos devem utilizar a mesma unidade funcional e considerações metodológicas equivalentes. Diferenças quanto às fronteiras dos sistemas, qualidade dos dados, procedimentos de alocação, regras de decisão na avaliação de entradas e saídas e avaliação de impactos devem ser identificadas e relatadas. Além disso, ao final de uma ACV, pode-se optar pela realização de uma revisão crítica, que nada mais é que do que uma verificação de que o estudo satisfez a norma que rege sua elaboração. Deve estar descrito no escopo "se", "como" será conduzida esta revisão, bem como, quem será o responsável por sua realização.

2.5.1. Análise de Inventário de Ciclo de Vida

Esta etapa envolve a coleta de dados e os procedimentos de cálculo para quantificar entradas e saídas pertinentes a um sistema de produto. A qualidade e a consistência dos dados são questões chave, portanto, essa pode ser a etapa mais trabalhosa do desenvolvimento de uma ACV (Finnveden et al., 2009).

A não disponibilidade de dados, a qualidade dos dados disponíveis e a necessidade de realizar estimativas podem comprometê-la e torná-la uma das tarefas mais complexas a ser desenvolvida.

A elaboração de uma análise de inventário é um processo iterativo, pois na medida em que se conhece mais o sistema, novos requisitos ou limitações podem ser identificados. Nesses casos pode ser necessário alterar os procedimentos de coleta de dados, mas os objetivos devem ser garantidos. Entretanto, algumas vezes é necessário rever até mesmo os objetivos, e o escopo, o que implica em revisões na primeira etapa do estudo, mas não impede sua realização (ISO, 2006a).

Alguns procedimentos podem auxiliar no desenvolvimento do inventário (ISO, 2006b):

a) Construção de fluxogramas gerais de processo que ilustrem os processos elementares e suas inter-relações;

b) Descrições detalhadas de cada processo elementar com relação aos fatores que influenciam as entradas e saídas;

c) Lista de fluxos e dados relevantes para as condições associadas a cada processo elementar;

d) Determinação das unidades de medida utilizadas;

e) Determinação dos métodos de coleta e cálculo para todos os dados;

f) Provisão de instruções para documentação de casos especiais, irregularidades ou outros itens associados aos dados fornecidos.

Depois de identificadas as unidades de processo que compõem o sistema, dados qualitativos e quantitativos devem ser coletados para cada uma. As restrições práticas à coleta devem ser devidamente consideradas no escopo do estudo e documentadas no relatório.

Para os cálculos, existem algumas considerações importantes, principalmente quanto aos procedimentos de alocação, ou seja, a repartição dos fluxos de entrada ou de saída de uma unidade de processo no sistema de produto sob estudo (Standard, 2006a, 2006b).

Assim, esses procedimentos são necessários quando se estudam sistemas que envolvam produtos múltiplos (como o refino do petróleo). Uma vez que esses produtos estão relacionados ao sistema de produto, é justo que a influência nos aspectos ambientais do sistema seja dividida.

Nesse sentido, a alocação busca criar um método de distribuição das contribuições aos impactos entre os diferentes resultados do sistema (Monteiro and Freire, 2012). Os fluxos de materiais e energia, assim como as liberações ao ambiente devem ser alocados aos diferentes produtos do sistema de acordo com procedimentos claramente estabelecidos, documentados e justificados.

A alocação deve ser preferencialmente evitada, mas nem sempre isso é possível (Dreyer et al., 2003). Sempre que diversas alternativas de procedimentos de alocação parecerem aplicáveis, uma análise de sensibilidade deve ser conduzida para explicitar as consequências da substituição da abordagem selecionada (ISO, 2006b).

2.5.2. Avaliação do Impacto de Ciclo de Vida

O inventário lista o consumo de recursos e as emissões associadas ao processo estudado, mas é preciso considerar que nem todos os itens listados terão o mesmo impacto no ambiente. Com base na listagem de recursos consumidos e emissões apresentada no inventário deve-se verificar a significância dos impactos ambientais potenciais. A Figura 7 ilustra o processo de transformação dos dados do inventário em impactos ambientais (Manfred and Pant, 2011).

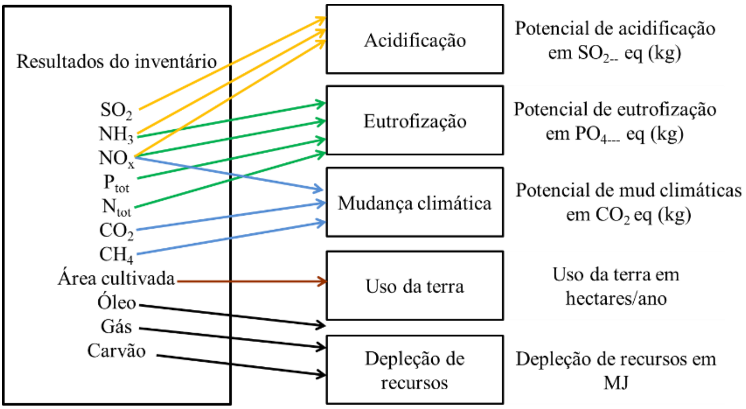

Figura 7: Dados de inventário correlacionados aos impactos gerados. (Manfred and Pant, 2011).

Cada impacto é calculado multiplicando-se a quantidade de cada item no inventário por um fator de avaliação de impacto, que é uma medida de quão profundamente cada um contribui para cada categoria de impacto (Ashby, 2009), conforme demonstrado na Equação 1 (Williams, 2009).

Dados do inventário x Fator de avaliação = Magnitude do impacto (1)

Os impactos resultantes de determinada atividade podem ser divididos em categorias, tais como: mudanças climáticas, depleção da camada de ozônio, toxicidade humana, acidificação, eutrofização, efeitos respiratórios, ecotoxicidade, uso da terra e depleção de recursos (Chen et al., 2010; Manfred and Pant, 2011; Williams, 2009).

Também existem muitos métodos disponíveis para realização da avaliação de impactos e a escolha de um deles nem sempre é óbvia. Apesar da semelhança entre alguns deles, algumas diferenças importantes podem levar a resultados divergentes (Dreyer et al., 2003).

A principal delas é que alguns métodos são baseados em uma abordagem de *midpoint* enquanto outros são baseados em uma abordagem de *endpoint*. Essa diferença é ilustrada na Figura 8, mas basicamente, as abordagens de *midpoint* utilizam um maior número de categoria de impactos e os resultados são mais exatos e precisos se comparados às três “áreas de proteção” comumente utilizadas nas abordagens de *endpoint* (Centre, 2010).

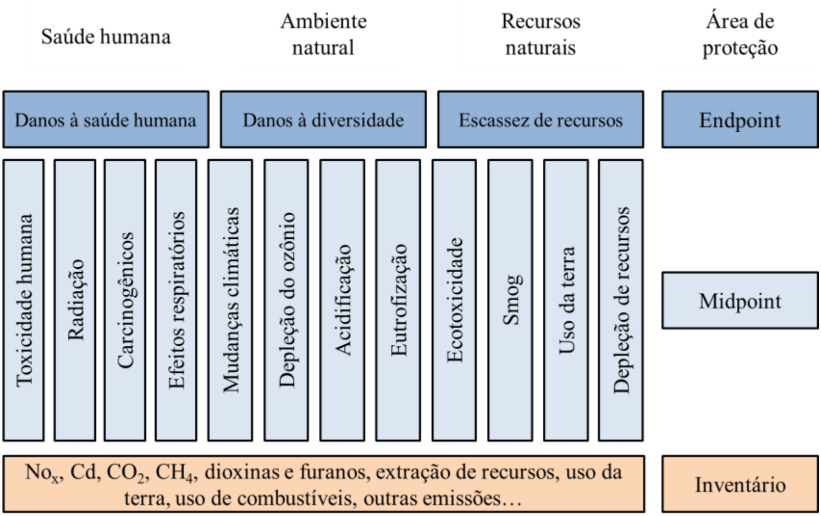

Figura 8: Abordagens midpoint e endpoint.
Adaptado (JRC, 2010).

2.5.3. Interpretação

Pode ser considerada uma das etapas mais sensíveis, pois as hipóteses estabelecidas durante as fases anteriores, assim como as adaptações que podem ter ocorrido em função de ajustes necessários afetam diretamente o resultado final do estudo.

Ao final, deve ser elaborado um relatório que possibilite a utilização dos resultados e sua interpretação de acordo com os objetivos estabelecidos para o estudo. Deve-se responder a questões como 'o que o inventário e os valores atribuídos a cada impacto representam'? 'O que pode ser feito para reduzir esses impactos?'(Ashby, 2009). O desenvolvimento da interpretação deve ser realizado conforme os tópicos que seguem (Standard, 2006b):

a) Identificação das questões significativas com base nos resultados das fases de inventário, avaliação de inventário e avaliação do ciclo de vida;
b) Uma avaliação do estudo, considerando verificações de completeza, sensibilidade e consistência;
c) Conclusões, limitações e recomendações.

2.5.4. Elementos Opcionais em uma ACV

Além das etapas descritas anteriormente, podem ser realizadas ainda: normalização, , ponderação e análise da qualidade dos dados (ISO, 2006a, 2006b).

A normalização é o cálculo da magnitude do resultado do indicador da categoria em relação à uma informação de referência, ou seja, o resultado obtido para cada categoria de impacto é dividido por um respectivo valor de referência previamente selecionado. Desta maneira, a normalização é uma base para comparação de diferentes tipos de categorias de impacto, uma vez que, normalizados os resultados, todos passam a ser adimensionais (Manfred and Pant, 2011). A escolha deste valor de referência afetará diretamente o resultado da normalização, portanto sua seleção deve ser criteriosa e condizente temporal e espacialmente com o sistema em estudo (Standard, 2006b). Além disso, resultados normalizados refletem a contribuição do produto analisado para o impacto potencial total, e não a severidade/relevância do impacto total respectivo. Assim, resultados normalizados, apesar de adimensionais, não devem ser somados (Manfred and Pant, 2011).

Para análise da relevância dos impactos analisados, a ponderação é o procedimento mais indicado. Os resultados, eventualmente já normalizados, são multiplicados por fatores de ponderação selecionados, gerando uma indicação da prioridade a ser dada a cada categoria de impacto. Entretanto, não há base científica para a realização dessas análises e elas não estão disponíveis em alguns métodos de avaliação (Pré Consultants, 2014).

Por ser uma metodologia relativamente nova, e em desenvolvimento, os estudos de ACV continuam sendo descrições imperfeitas do sistema de produção. Pela complexidade envolvida nos estudos de ACV, existe um potencial de incerteza relacionado à qualidade dos dados, e mesmo involuntariamente, certa subjetividade pode estar presente nesses apontamentos.

Uma maneira de considerar o quanto os dados obtidos interferem nos resultados é realizar a análise de sensibilidade, o que é especialmente indicado em estudos comparativos. A análise de sensibilidade é um procedimento para estimar os efeitos das escolhas feitas em relação aos dados e métodos escolhidos nos resultados de um estudo (ISO, 2006b)

Assim, com o intuito de tornar o estudo mais fiel à realidade, e evitar manipulações, abusos na condução, ou mesmo erros involuntários, é sugerido que seja realizada uma revisão crítica ao final do trabalho. Isso deve ser definido no escopo, bem como é indicado identificar por que será realizada, sua abrangência e seu grau de detalhamento (ISO, 2006a).

Essa revisão tem por objetivo assegurar que os métodos utilizados para conduzir a ACV são consistentes com a norma, que os métodos utilizados são científica e tecnicamente válidos, que os dados são apropriados e razoáveis em relação ao objetivo do estudo, que as interpretações refletem de maneira transparente e consistente o sistema estudado.

Quando os estudos de ACV serão utilizados para apoiar informações comparativas, a revisão crítica é especialmente interessante, uma vez que esta aplicação pode afetar partes interessadas que são externas ao estudo. Nesse sentido, a revisão crítica servirá para diminuir a probabilidade de mal-entendidos ou efeitos negativos em relação a partes interessadas externas, entretanto, sua realização não implica de modo algum em apoio a qualquer tipo de afirmação comparativa que seja realizada.

Sua realização pode ser conduzida por um especialista interno ou externo. No primeiro caso, este especialista pode ser interno à organização, mas deve ser externo à realização do estudo. Quando há mais de uma parte interessada no estudo, é conveniente que o especialista seja externo. Nesse caso, ele é selecionado pelo solicitante original do estudo para agir como coordenador de uma comissão de revisão crítica, e aí então, ele escolhe sua equipe, sendo selecionados outros analistas qualificados e independentes. Essa comissão também pode incluir demais partes interessadas, como agências governamentais, grupos não governamentais ou concorrentes.

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3. METODOLOGIA

3.1. Cenários Estudados

Foram estudados três diferentes cenários de produção de cimento, denominados “Empresa Europa”, “Estimativas Brasil” e “Empresa Brasil”. O cenário “Empresa Europa” foi baseado em dados primários para uma empresa do sudoeste europeu, enquanto o cenário “Estimativas Brasil” foi baseado em dados secundários para a indústria de cimento brasileira. O cenário “Empresa Brasil” foi baseado em dados primários de uma empresa do sul do Brasil, complementados com dados secundários quando houve necessidade.

A avaliação de impactos foi conduzida pelos métodos de avaliação de impactos CML 2001(Institute of Environmental Sciences, 2013) e Recipe, porém o método CML 2001 foi aplicado somente ao cenário “Empresa Europa”, a título de comparabilidade com demais estudos já desenvolvidos na região. Além disso, o método Recipe foi desenvolvido por profissionais que também participaram do desenvolvimento do método CML 2001. Assim, o método Recipe, desenvolvido no ano de 2008, é mais aceito na comunidade científica, pois representa uma harmonização entre o método CML 2001 e outros métodos anteriores, como o Eco-indicator 99. O nome “Recipe”, além de fazer uma alusão à “receita” utilizada para o cálculo dos indicadores das categorias de impacto, representa as iniciais dos institutos os quais foram os principais colaboradores no seu desenvolvimento: RIVM, Universidade Radboud, CML e PRé Consultants (Goedkoop et al., 2012).

Para os dois métodos, os fatores de impacto e as metodologias de avaliação são atualizadas sempre que necessário, o que gera uma série de versões diferentes de cada método. Neste trabalho foram utilizados o método CML 2001 versão 2.05 e Recipe Midpoint H versão 1.06.

Etapas associadas à produção do cimento, mas não analisadas diretamente neste estudo (por exemplo, a extração das matérias primas, dos combustíveis fósseis, transportes e eletricidade) foram baseadas no banco de dados Ecoinvent versão 2.2 (Ecoinvent, 2010)e todos os cálculos foram realizados com o software Simapro versão 8.0.3.14 (Pré Consultants, 2014).

3.2. Metodologia Geral

Em todos os cenários estudados a unidade funcional foi a produção de uma tonelada de cimento. A metodologia geral aplicada neste estudo é demonstrada na Figura 9. O levantamento do inventário de cada cenário foi considerado parte dos resultados, por isso é apresentado no capítulo seguinte. Os impactos analisados pelo CML 2001 e pelo Recipe são apresentados na Tabela 4, com as respectivas grandes áreas de proteção e as unidades de medição. Na apresentação dos resultados, esses impactos estão agrupados em "impactos atmosféricos", "impactos de toxicidade" e "demais impactos".

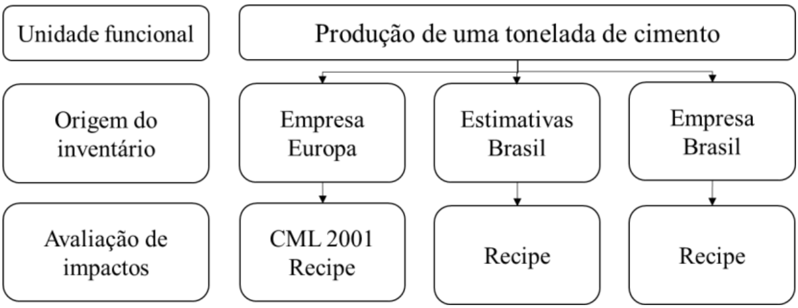

Figura 9: Procedimento metodológico geral deste trabalho.

Por último, para fins comparativos, foram realizadas a normalização dos dados de todos os cenários estudados e uma análise de sensibilidade para os aspectos relativos à geração de energia elétrica. Também se verificou a necessidade de desenvolver uma análise de sensibilidade para o cenário "Empresa Brasil", em decorrência dos resultados que serão adiante apresentados.

Tabela 4: Impactos analisados segundo os métodos CML 2001 e Recipe.

<table>
<tr><th colspan="3">CML 2001</th><th colspan="4">Recipe</th></tr>
<tr><th>Área de proteção</th><th>Categoria de impacto</th><th>Unidade</th><th>Grande área de proteção</th><th>Categoria de impacto</th><th>Unidade</th><th>Agrupamento</th></tr>
<tr><td rowspan="2">Disponibilidade de recursos</td><td rowspan="2">Potencial de depleção abiótica</td><td rowspan="2">[kg Sb-eq.]</td><td rowspan="3">Diversidade de ecossistemas
Saúde humana</td><td>Mudanças climáticas</td><td>kg CO_2 eq</td><td rowspan="4">Impactos atmosféricos</td></tr>
<tr><td>Depleção do ozônio</td><td>kg CFC-11 eq</td></tr>
<tr><td rowspan="4">Diversidade de ecossistemas</td><td rowspan="2">Potencial de acidificação</td><td rowspan="2">[kg SO_2-eq.]</td><td>Formação de oxidantes fotoquímicos</td><td>kg NMVOC</td></tr>
<tr><td>Saúde humana</td><td>Formação de material particulado</td><td>kg PM_{10} eq</td></tr>
<tr><td rowspan="2">Potencial de eutrofização</td><td rowspan="2">[kg PO_4-eq.]</td><td rowspan="3">Diversidade de ecossistemas</td><td>Acidificação terrestre</td><td>kg SO_2 eq</td><td rowspan="5">Demais impactos</td></tr>
<tr><td>Eutrofização de água doce</td><td>kg P eq</td></tr>
<tr><td rowspan="3">Saúde humana</td><td rowspan="3">Potencial de aquecimento global</td><td rowspan="3">[kg CO_2-eq.]</td><td>Eutrofização marinha</td><td>kg N eq</td></tr>
<tr><td>Disponibilidade de recursos</td><td>Depleção de metais</td><td>kg Fe eq</td></tr>
<tr><td>Disponibilidade de recursos</td><td>Depleção fóssil</td><td>kg oil eq</td></tr>
<tr><td rowspan="4">Saúde humana</td><td rowspan="4">Potencial de formação de oxidantes fotoquímicos</td><td rowspan="4">[kg C_2H_4-eq.]</td><td>Saúde humana</td><td>Toxicidade humana</td><td>kg 1,4-DB eq</td><td rowspan="4">Impactos de toxicidade</td></tr>
<tr><td rowspan="3">Diversidade de ecossistemas</td><td>Toxicidade terrestre</td><td>kg 1,4-DB eq</td></tr>
<tr><td>Toxicidade de água doce</td><td>kg 1,4-DB eq</td></tr>
<tr><td>Toxicidade marinha</td><td>kg 1,4-DB eq</td></tr>
</table>

Adaptado de (Goedkoop et al., 2012; Institute of Environmental Sciences, 2013).

3.3. Referências

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4. RESULTADOS E DISCUSSÃO

This section is presented mostly in the form of papers, reason why a number of important information can be repeated.

The first paper, “Life cycle assessment of the production of Portland cement: A Southern Europe case study”, refers the situation of an “European Union Company” studied through LCA method CML 2001. This paper was based on CML 2001 in order to allow comparison to other studies for the region.

The second section presents a discussion of the results obtained to the same scenario, however, based on Recipe method, as shown in the title: “Comparison between CML 2001 and Recipe method based on European Union Company”. However, it is important highlighting that not all categories of impact are comparable, so that still in this section, an “Analysis of European Union Company Scenario through Recipe method” presents the results of further impact categories analyzed according to Recipe method.

The third section presents the paper “Life Cycle Assessment Applied to the Brazilian Cement Production”, that details the scenario “Brazil Estimatives” through Recipe method, and is based on public data and estimatives to the year 2013.

The paper presented in the fourth section, “Life Cycle Assessment of the Production of Cement: A Brazilian Case Study” refers to the scenario “Brazilian Company”, and it is also analyzed through Recipe method and submitted.

Finally, in the last section, we present further considerations regarding some aspects of energy and transports, as well as normalization analysis.

4.1. Life Cycle Assessment of the Production of Portland Cement: A Southern Europe Case Study[3]

4.1.1. Introduction

The construction sector generates several environmental problems and the use of sustainable building materials has become the main focus of research and development in achieving the goal of

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sustainable construction (Pacheco-Torgal et al., 2014). In this regard, Esin (Esin, 2007) and Franzoni (Franzoni, 2011) state that sustainable building materials are those manufactured following resource and energy efficiency principles, which should pollute less and have no negative impact on human health.

In this context, it is very important to understand the environmental impacts of cement production, since it is the main component of concrete, the most consumed material on Earth (WBCSD, 2009b). The worldwide cement production reached 3.6 billion tonnes in 2012 and it is projected to grow by 0.8-1.2% per year, reaching between 3700 and 4400 megatonnes in 2050 (CEMBUREAU, 2012; WBCSD, 2009a).

The key component of cement is clinker, a mixture of nodules and lumps of tri and dicalcium silicates (alite and belite), tricalcium aluminate, and tetracalciumaluminoferrite, which is produced by sintering of calcium oxide, aluminosilicates and other raw materials (Martos and Schoenberger, 2014). This process is based on the decomposition of calcium carbonate into calcium oxide, which causes high carbon dioxide (CO2) emissions, in addition to those associated with burning of fossil fuels. Fig. 10 shows a typical flowchart of ordinary Portland cement production.

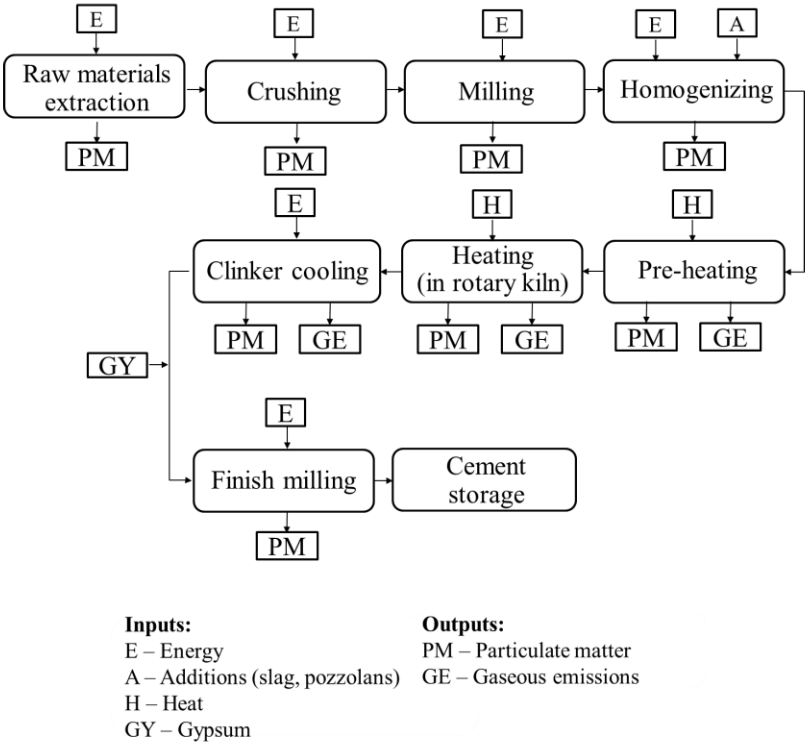

Figure 10: Process flow diagram for the manufacture of cement. Adapted from Huntzinger et al. (Huntzinger and Eatmon, 2009).

In 2011, about 2.6 gigatonnes of CO2 were emitted globally due to cement production, wherein half of these emissions were due the calcination of limestone and the other half were due to the combustion of fossil fuels (A. P. Gursel et al., 2014). In addition, a huge supply of electricity is required for grinding the raw materials and the clinker/cement (Edenhofer et al., 2012). These aspects make the cement industry responsible for approximately 12-15% of the total industrial energy use (Madlool et al., 2011) and to 5-7% of anthropogenic CO2 emissions (Fry, 2013b). Actually, each tonne of produced Portland cement releases almost one tonne of CO2 to the atmosphere (Meyer, 2009), but this value can vary with the location, technology, production efficiency, mix of energy sources used in electricity generation and the selection of kiln fuels (A. P. Gursel et al., 2014). Therefore, a significant effort has been made to lower energy demands and CO_2 emissions (CEMBUREAU, 2009; FICEM, 2012; Madlool et al., 2011; Meyer, 2009). According to Schneider et al. some options to be considered are reducing the amount of clinker in cement, using waste as raw material and fuel, and improving the efficiency of current technology (Schneider et al., 2011).

Among those alternatives, the use of wastes as raw materials and fuels is called co-processing and is well implemented in many places worldwide. The most common wastes are tires, wood waste, plastics, meat and bone animal meal, municipal waste as refuse derived fuel (RDF), sewage sludge, and textiles. In the European Union (EU), the thermal substitution ratio in cement kilns increased from 3% in 1990 to 16.7% in 2004. In fact, countries like Austria, Germany and Norway reached substitution ratios above 60%. In 2010-2011, The Netherlands reached a replacement ratio of 83%, while the average for EU was about 30%. Those numbers confirm the capacity of the cement industry for co-processing wastes (Aranda Usón et al., 2013).

Many studies have been conducted aiming to assess the environmental impacts of such practice, but the results can vary according to the applied methodology and processing variables, such as raw materials composition, fuels, available technology, among others (Lamas et al., 2013; Martos and Schoenberger, 2014).

One of the most common methodology employed to evaluate the environmental impacts is Life Cycle Assessment (LCA), an extended method with an holistic approach that guarantees the comprehensiveness of an environmental evaluation and ensures its reproducibility (ISO 14040, 2006). This methodology is a structured and standardized method, which quantifies all relevant emissions and resources consumed, the related environmental and health impacts, as well as resource depletion issues that are associated with any goods or services (Centre, 2010).

According to Gursel et al. (A. P. Gursel et al., 2014), a critical step in any LCA is the compilation of a credible life cycle inventory (LCI), upon which subsequent life cycle impact assessment (LCIA) can be based. Martos and Schoenberger (Martos and Schoenberger, 2014) found that the average LCA study conducted for assessing the impacts of using RDF in cement plants is a simplified calculation of the global warming potential. Moreover, final results strongly depend on the initial assumptions and have a non-negligible degree of uncertainty.

Other authors studied the environmental impact of the French cement production and its variations among different plants through LCA (Chen et al., 2010). They found oscillations between 20 and 30% for indicators controlled by kiln emissions, such as global warming and photochemical oxidation. For acidification and eutrophication, the variations were greater than 40%. The authors attributed those uncertainties to difficulties on performing or getting accurate measurements of both pollutant contents and annual flows.

In this way, we realize the need to develop LCA studies based on primary data collected directly from the manufacturing plant, as complete as possible. Since each step of production can present different significances of environmental impacts, we believe that LCA studies based on secondary data are just indicatives of production hotspots. However, the conclusions can vary according to particularities of each factory.

Thus, in this context, we assess the environmental impacts of a cement manufacturing producer with co-processing of wastes. This LCA is based on data collected from a cement plant in Southern Europe, which is responsible for the production of 4 million tonnes of cement per year. In this analysis, not only global warming potential is assessed as an indicator of cement production environmental damage, but also abiotic depletion, acidification, eutrophication and photochemical oxidation potentials are also taken into account.

4.1.2. Methodology

There is not a single method to carry out LCA studies. ISO 14040 recognizes that organizations must have the flexibility to implement LCA in accordance with the intended application and their own requirements (ISO 14040, 2006). Nevertheless, some steps should be followed: (1) definition of goal and scope; (2) inventory analysis; (3) impact assessment and (4) interpretation. The first three steps are detailed below. The interpretation corresponds to the Results and Discussion Section.

Goal and scope

The goal was to assess environmental impacts of using wastes as fuel in the cement manufacturing based on primary data from a process plant in Southern Europe. A process flowchart is shown in Fig. 11 in order to identify main inputs and outputs concerning this activity. The functional unit is one tonne of ordinary Portland cement. Within the boundaries of the system are extraction and processing of raw materials and fossil fuels, alternative fuels supply, all transport steps involved and the unit operations required to produce the cement at the manufacturing plant. Capital goods were included.

RDF and scrap tires were used as alternative fuels partially replacing fossil fuels. Plastic and rubber, polyurethane foam and industrial wastes represent, together, less than 1% of the alternative fuels composition and were therefore not included in this study. The impact of RDF preparation (milling and homogenizing of municipal solid waste) was not considered. Moreover, the processing of wastes generated in the cement production was not included in this study due to the low amount and to the fact that most part of these wastes is reused in the processing plant.

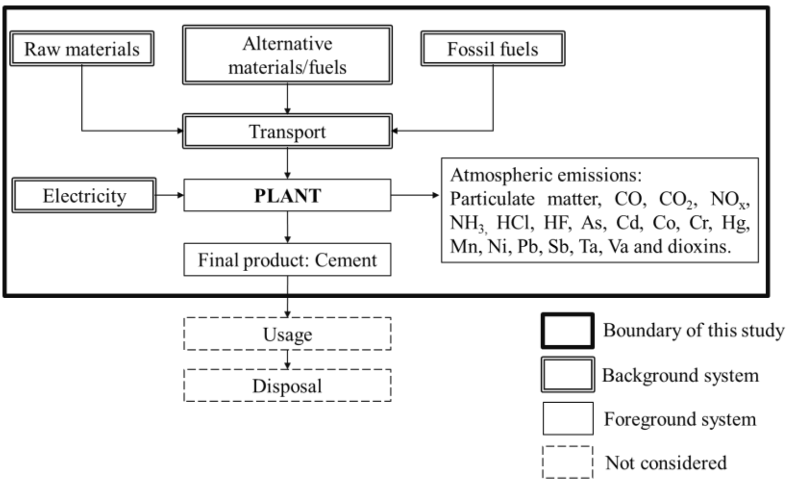

Figure 11: System boundaries of the LCA of a cement plant in Southern Europe.

Inventory analysis

Inventory data for the foreground system were taken directly from the studied industrial unit, located in Portugal, Southern Europe, and is based on the year of 2013. Due to confidentiality issues, some data cannot be directly disclosed. Inventory data corresponding to the background system (raw materials extraction, fossil fuels obtaining and electricity production) were taken from the Ecoinvent database (Frischknecht R. et al., 2005). Although the last update of the Ecoinvent version used in this study was in 2010 (Ecoinvent, 2010), the database available for energy generation scenarios correspond to year 2000. Nevertheless, it is important to stress that in this meantime the electricity generation matrix in Portugal has changed from 43,764 GWh (73% thermal power) in 2000 to 51,672 GWh (47% thermal power) in 2013, according to Pordata (Pordata, 2015). Thus, the energy generation in this country has increased significantly towards renewable sources (29% hydropower, 23% wind power, 1% photovoltaics in 2013), which was not taken into account and may cause some bias in the current analysis.

Inputs considered were calcareous marl, limestone, sand, gypsum, water, electricity, petroleum coke, and heavy fuel oil. End-of-life tires and RDF were used as alternative fuels with a replacement ratio of 43% in relation to the fossil fuels. The main outputs are related to air emissions from the kiln and include dust, carbon monoxide, carbon dioxide, nitrogen oxides, hydrogen fluoride, hydrogen chloride and sulphur dioxide. Electricity used to crushing and grinding raw materials and emissions from the mills are also included as inputs and outputs, respectively. It is important to highlight that the factory has installed a bypass in order to remove chlorine from the process, which is one of the major obstacles to the use of wastes as fuels. Other pollutants that cannot be continually monitored are punctually measured according to local regulations, such as antimony, arsenic, lead, chromium, cobalt, copper, manganese, nickel, vanadium, dioxins and furans. The transportation of raw materials and fuels was based on the actual distances between suppliers and the factory, but its impact was estimated as a background system. All materials and infrastructure requirements to develop the production steps were also considered.

Impact Assessment

Life Cycle Impact Assessment was conducted using a database for characterization factors of life cycle impact assessment, which was developed by the Centrum voor Milieuwetenschappen Leiden (CML) (Institute of Environmental Sciences, 2013).

The evaluated impact potentials were abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP) and photochemical oxidation potential (POP). The choice of these impact categories is based on the fact that they are mostly affected by the substances referred in the inventory. Moreover, these five impact categories cover local, regional and global impacts from cement manufacture. The system of cement production presented in Fig. 11 was divided into five steps: raw materials extraction, fossil fuels production, transportation, electricity and clinkering. The results obtained for each impact category were assessed according to those five steps. All calculations have been performed with the LCA software SimaPro (Prè, 2014).

In order to compare those results to other studies (Chen et al., 2010; Josa et al., 2007, 2004), the impact assessment was conducted based on the same database (CML 2001, last updated in 2013). The impact categories evaluated were abiotic depletion, due to the intensive use of raw materials and fossil fuels, and acidification, eutrophication, global warming and photochemical oxidation, due to the atmospheric emissions from the clinkering and other emissions associated to the electricity generation and transports involved.

4.1.3. Results and Discussion

The impact assessment results for each step considered in the cement manufacture are shown in Fig. 12 and the absolute values for each impact category are presented in Table 5. The fossil fuel production step is the main contributor to ADP, but it is important to consider that petroleum coke is responsible for 99% of the measured impact potential. However, electricity production has also a relevant effect on this impact category, due to the use of fossil fuels (coal and natural gas combustion in thermal power plants) in their production.

For the remaining impact categories, the atmospheric emissions from the clinkering have the largest contribution. This was expected especially for GWP due to CO2 emissions associated to the calcination reaction (Equation 2):

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (2)$$

This reaction is responsible for approximately 60% of the CO2 emissions from the kiln, which corresponds to 83.2% of CO2 equivalent emitted by this system. GWP is the impact category most discussed in cement production studies. According to Pacheco-Torgal et al. (Pacheco-Torgal et al., 2014), over the last decades, the emphasis has clearly shifted towards a global focus on climate change. In general, it is stated that each tonne of cement produces 0.6–1.0 tonne of CO2 to the atmosphere (Feiz et al., 2014a; Huntzinger and Eatmon, 2009; Pacheco-Torgal et al., 2014; Uwasu et al., 2014; Valderrama et al., 2012). However, many actions have been taken in the last years, trying to avoid this amount of carbon dioxide. Among those actions are the reduction of clinker ratio in the cement and the use of newest technologies and alternative fuels. In this study, we found 0.632 tonne of CO2-eq for each tonne of cement, including raw materials and fossil fuels processing, electricity production, transports and atmospheric emission from the clinkering.

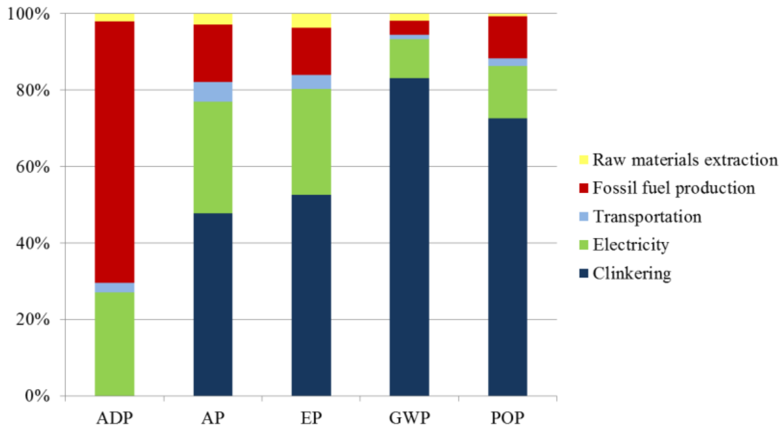

Figure 12: Contribution of each processing step to the studied impacts.

Table 5: Impact assessment of 1 tonne of cement according to CML 2001.

Impact	Unit	Total
ADP	[kg Sb-Eq]	1.81×10^{0}
AP	[kg SO_2-Eq]	1.97×10^{0}
EP	[kg PO_4-Eq]	3.54×10^{-1}
GWP	[kg CO_2-Eq]	$6.32 \times 10^{+2}$
POP	[kg C_2H_4-Eq]	1.58×10^{-1}

Besides those atmospheric emissions, the electricity step also contributes to all other impacts categories, but in minor intensity: approximately 29.2% of total AP and 27.6% of total EP.

Concerning AP, most of the total impact derives from the kiln emissions, which correspond to ~48% of the total. In this specific case, most of the SO2 emissions arise from the kiln due to fuel combustion and to the processing of the raw material in the kilns (Pacheco-Torgal et al., 2014). In fact, SO2 results from the oxidation of sulphide or elemental sulphur contained in the fuel or in raw materials when there is sufficient oxygen and the material temperature is in the range of 300 to 600ºC (Basel Convention, 2011).

The end-of-life tires used in this process are also an additional source of sulphur, which is used in the vulcanization process (Feraldi et al., 2012). However, due to the alkaline matrix of the clinker, the presence of sulphur in alternative fuels does not result in critical levels of gaseous emissions. Moreover, sulphur concentration in RDF is much lower than the reference value in fossil fuels (0.1–0.2% in RDF; 3–5% in fossil fuels) (Genon and Brizio, 2008). In addition, there is an important contribution to achieve lower nitrogen compounds emissions, which also significantly affects AP impact category.

Indeed, end-of-life tires can also deliver a significant contribution to the reduction of nitrogen oxide emissions (CEMBUREAU, 2009), which are highly dependent on the temperature and oxygen availability in the kiln. It occurs because the use of end-of-life tires reduces significantly the amount of gas that pass through this zone of NOx formation (Richards et al., 2008). Moreover, the formation of NOx is also related to the amount of nitrogen in the fuel and the residence time. In general, the nitrogen content can vary from 0.3–0.5% in RDF against 1.5–2.0% in fossil fuels (Genon and Brizio, 2008; Pacheco-Torgal et al., 2014).

Regarding the other cement production steps, electricity production is responsible for 29.2% of AP, followed by fossil fuels obtaining (15%), wherein petroleum coke is the main cause due to the amount used.

From Fig. 12 it is possible to verify that EP causes are very similar to AP causes. The atmospheric emissions from the clinkering contributes to 52.6% of EP, while electricity and fossil fuel obtaining corresponds to 27.7% and 12.3%, respectively. The last analyzed category, POP, is mostly influenced by the clinkering (72.6%), followed by electricity (13.6%) and fossil fuels obtaining (10.9%).

As those last three categories are influenced by nitrogen and sulphur compounds, it is natural that the atmospheric emissions from the clinkering contribute the most. Besides this, carbon compounds also influence POP, which is present in these emissions.

Some important discrepancies must be highlighted when comparing the absolute values presented on Table 5 to previous studies regarding LCA of cement production. Chen et al. (Chen et al., 2010) studied environmental impact of French cement production, based on this same life cycle impact assessment method (CML 2001). The referred study does not include the transportation of alternative fuels and input data were based on values reported by the French cement producers union, while output data correspond to mean values collected from 15 cement companies with similar production conditions to those analyzed in this paper. In addition, their functional unit was 1 kg of cement. Table 6 compares the impact assessment obtained by (Chen et al., 2010) to the impact assessment presented in this study.

Table 6: Impact assessment results according to CML 2001 compared to the literature (Chen et al., 2010).

Impact	**Unit**	**Chen et al. (2010)**		**This study**[1]
		Mean	**Standard Deviation**	
ADP	[kg Sb-eq.]	243×10^{-3}	no data	1.81×10^{-3}
AP	[kg SO_2-eq.]	3.49×10^{-3}	1.54×10^{-3}	1.97×10^{-3}
EP	[kg PO_4-eq.]	5.04×10^{-4}	2.20×10^{-4}	3.54×10^{-4}
GWP	[kg CO_2-eq.]	7.82×10^{-1}	1.41×10^{-1}	6.32×10^{-1}
POP	[kg C_2H_4-eq.]	1.11×10^{-4}	3.17×10^{-5}	1.58×10^{-4}

[1]Converted to a functional unit of 1 kg of cement.

Because this study is based on primary data, we expected lower impact values, what happened to all impact categories compared (except for POP, which is a little larger in this study) but within the same order of magnitude. Surprisingly, ADP is much lower than that found by Chen et al. (Chen et al., 2010). Although secondary data are oversized many times, this difference is very large and difficult to explain, but we agree that most part of this impact is caused by primary fuel production

(68.4% in this case, against almost 90% to Chen et al. (Chen et al., 2010)).

Regarding AP and EP, Chen et al. (Chen et al., 2010) also found similar profiles, just as in this study, and the main contributors are the atmospheric emissions from the clinkering. However, the second largest contribution according to this study, electricity, is not separately analyzed by those authors (Chen et al., 2010), hindering further considerations.

According to Chen et al. (Chen et al., 2010), the atmospheric emissions from the clinkering are responsible for 88.6% of GWP, while in this study this value is 83.2%. They also took into account the use of wastes as alternative fuels; however, this procedure was not detailed. Thus, we cannot affirm that the lower values found occur because of the RDF usage.

Another important consideration is that related to the data source: Chen et al. (Chen et al., 2010) reported mean impact values. AP and EP are particularly relevant because in these cases the standard deviations were close to the corresponding mean values. That large uncertainty was attributed by the authors to difficulties in getting accurate measurements, which reduces the validity of the final result, and reinforces the need to assure quality data in the development of an LCA study.

Josa et al. (Josa et al., 2004) analyzed a number of LCA studies related to cement production in EU and reported that the clinker production (fuel combustion and calcination reaction) and the energy consumed throughout the whole production process (clinker and cement) are responsible for the emission of 800 kg CO_2/tonne of cement. In this case, other emission sources, such as fuel usage during material extraction or fuel usage for transports were not considered. They also reported that the percentages of CO_2 emissions corresponding to cement production are 59% due to chemical reactions from clinker production, 35% due to the total fuel consumption of each stage and 6% due to other stages of the whole system. These numbers are quite similar to those found in this study, which are ~57% due to chemical reactions from clinker production, 37% due to fuel consumption of each stage, and 6% due to other stages of the whole system.

Another worth mentioning data come from Valderrama et al. (Valderrama et al., 2012). The authors studied a new cement production plant based on BAT (best available techniques) for a cement industry located at Catalonia (Spain) through a LCA approach. It is important to highlight that in this case the functional unit is 1 kg of clinker, so the values cannot be directly compared. Additionally, they did not take into account the use of alternative fuels. They found reductions of 14% to ADP, 15 and 17% to AP and EP, respectively, and 5% to GWP, attributed to the application of BAT in the cement plant.

According to the authors, the most significant improvements are related to energy efficiency in kiln system, representing less amount of fossil fuel required (meaning less emissions to the atmosphere) to produce one kg of clinker. Even so, absolute values of ADP, AP, EP, GWP found in the new plant are higher than those found in this study, even considering that our functional unit is based on the final product (cement) and their functional unit is based on the intermediary product (clinker).

Again, the exception is POP. Despite the different methodological issues, Valderrama et al. (Valderrama et al., 2012) and Chen et al. (Chen et al., 2010) present similar values to POP, lower than the value we found. In Fig. 13, the absolute values found for each impact category in this study are compared to the literature.

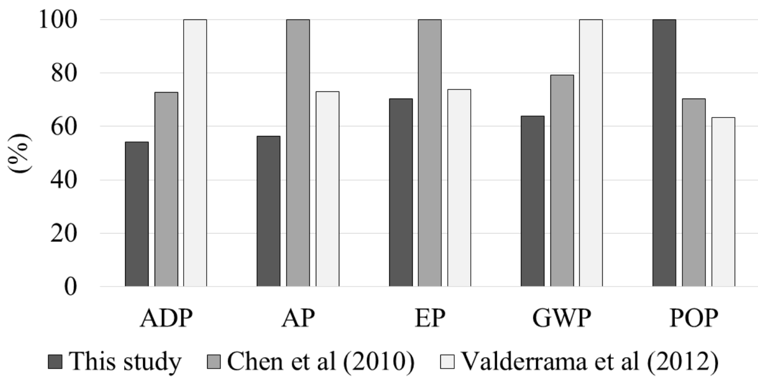

Figure 13: Comparison between absolute values of LCIA of cement production in different studies.

According to Ali et al. (Ali et al., 2011), the use of alternative wastes in cement kilns presents other benefits besides the reduction of atmospheric emissions (and consequently reduction of environmental impacts). Some of those benefits are listed as follows:

- Cost reduction of clinker production due to inexpensive fuel;
- Preservation of resources due to lower use of fossil fuel;
- No significant change of emissions;
- High thermal efficiency.

However, these advantages must be carefully interpreted. In our study, the use of alternative fuels allied to recent technologies has lower environmental impacts than the use of best available technologies, delivering lower atmospheric emissions in the clinkering process. Nevertheless, regarding organic pollutants, materials fed to the high temperature zone of the kiln system are nearly completely destroyed, but still part of the inorganic components are present in the clinker product and cement kiln dust. Additionally, the use of wastes in the clinker firing may change the metal concentrations in cement products, and depending on the total input through raw materials and fuels, the concentration of individual elements in the product may increase or decrease as a result of waste co-processing. Although most investigations have shown that the effect of waste on the heavy metals content of clinker is marginal on a statistical basis, there is an exception, which is the large use of tires that may raise zinc levels (Basel Convention, 2011).

Despite some methodological differences, it is a consensus that atmospheric emissions from the clinkering are mainly responsible for the cement industry impact. As demonstrated, these emissions are dependent of raw materials and fuels used, as well as of the factory technology. Therefore, the choice of raw materials and fuels has a direct impact on the relation between cement plants and the environment.

4.1.4. Conclusions

In this study, a LCA was carried out based on primary data collected from a cement industrial producer and background data from the Ecoinvent database. The atmospheric emissions from the clinkering contributed significantly to global warming and the other impact categories, except abiotic depletion. The contribution to global warming was expected due to the calcination of limestone, which is the main responsible for CO2 emissions. The results showed that the intensive consumption of raw materials and fossil fuels was the aspect that most affects the abiotic depletion potential. Fossil fuels production contributed significantly for acidification and eutrophication potential. Moreover, electricity consumption was also an important contributor to acidification potential, since fossil fuels are used in its generation.

The results obtained in this study seem to be in line or lower than those of other similar studies carried out in different EU countries. However, the entry values used in this study are based on primary data, which means more accuracy and reliability. Due to this, impact potential values presented here tend to be lower than values presented in other studies that used secondary data. The exception was POP.

Nevertheless, comparisons between LCA studies must be carefully performed, since some distinct methodological assumptions can influence the results. Moreover, the results may also depend on the technology level used in the cement plant and on the use of alternative fuels. In this way, we strongly suggest the use of real data, aiming to obtain impact assessment results that better represent real scenarios. Finally, we recommend further studies regarding the measurement of the efficiency of actions for environmental impacts mitigation and the use of energy efficient technologies for the kilns.

4.2. Comparative Analysis of the European Company

4.2.1. Comparison between CML 2001 and Recipe Methods based on Scenario "European Company"

To develop this scenario, all methodological procedures previously described to the scenario "European Union Company" was maintained. Only the analysis method was changed from CML 2001 (Institute of Environmental Sciences, 2013) to Recipe (Goedkoop et al., 2012).

As some metrics are not equal, not all results are comparable. There is also categories with different names, as Global Warming (CML 2001) and Climate Changes (Recipe); Ozone Layer Depletion (CML 2001) and Ozone Depletion (Recipe); or even Marine Aquatic Ecotoxicity (CML 2001) and Marine Ecotoxicity (Recipe). These differences, however, do not interfere in the data comparability, since the units are the same. Table 7 presents the absolute values of the impact categories that have similar units.

Table 7: Comparison between absolute values obtained by CML 2001 and Recipe method.

Impact categories	Unit	CML 2001	Recipe
Atmospheric impacts			
Climate change	kg CO_2 eq	6.32E+02	6.26E+02
Ozone depletion	kg CFC-11 eq	2.94E-05	2.98E-05
Resource depletion			
Terrestrial acidification	kg SO_2 eq	1.97E+00	1.99E+00
Toxicity			
Human toxicity	kg 1,4-DB eq	2.76E+02	4.16E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	8.62E-01	3.26E-02
Freshwater ecotoxicity	kg 1,4-DB eq	1.84E+01	5.15E-01
Marine ecotoxicity	kg 1,4-DB eq	5.59E+04	6.01E-01

Values for atmospheric impacts and resource depletion are similar. However, toxicity impacts evaluated through CML 2001 are superior than values obtained by the Recipe method. This occurs because, although the toxicity impacts in both methods be based on the Uniform System for the Evaluation of Substances (Van Zelm et al., 2009), the impact factors associated to the substances are different. Dioxins, for example, represented in this study by TCDD (2,3,7,8-tetrachlorodibenzo-p-dioxin, CAS 001746-01-6), have an impact factor of 1.93E+09 kg 1,4-DB eq, according to CML 2001. This value is superior than the 1.01E+08 kg 1,4-DB eq pointed by Recipe method.

Besides this, some substances, as, for example, Sulphur dioxide, presents contributions to impacts of human toxicity according to CML 2001 (9.6E-02 kg 1,4-DB eq) while are not considered by the Recipe method.

This occurs because the method CML 2001 used in this work is based on December 2007 data, and has been updated in November 2010 (Institute of Environmental Sciences, n.d.). By contrast, the Recipe method is newest and is based on information collected from 2008, therefore, most current and the last update was in July 2012 (Goedkoop et al., n.d.).

Due to this, further analysis presented in this thesis were carried out based on Recipe method.

4.2.2. Analysis of the European Company through Recipe Method

Table 8 presents the absolute values found for the atmospheric impacts according to Recipe (Goedkoop et al., 2012). Figure 14 presents the contribution of each unit of production to the referred impact categories.

Table 8: Absolute values to the impact categories to the scenario "European Company" through Recipe method.

Impact category	Unit	Total
Climate change	kg CO_2 eq	6.26E+02
Ozone depletion	kg CFC-11 eq	2.98E-05
Photochemical oxidant formation	kg NMVOC	1.76E+00
Particulate matter formation	kg PM_{10} eq	6.78E-01

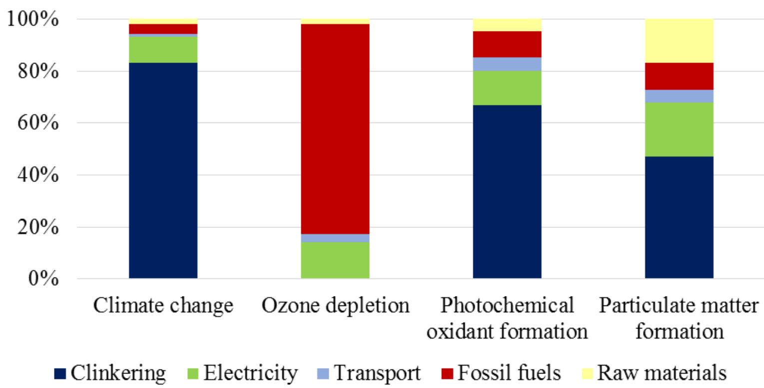

Figure 14: Contribution of each unit production to categories of atmospheric impacts according to Recipe method.

To the impact category of Climate change, the contribution profile of each unit of production is similar to that found by the CML 2001 method. In fact, this value is 0,9% superior to the one estimated according to the Recipe method (632 kg CO2 eq/kg of cement, against 626 kg CO2 eq/kg cement). In addition, the contribution profile of each unit of production remained similar: atmospheric emissions contributed to 83% of total, electricity is responsible for 10%, and the rest corresponds to minor contributions.

Similar fact occurs to Photochemical oxidant formation, that despite the different units used in the impact assessment methods, presented similar contribution profiles: 72% caused by clinkering and 13% by electricity, according to CML 2001, against 66% and 13% respectively, according to Recipe.

The categories ozone depletion and particulate matter formation were not analyzed according CML 2001, however, contribution profiles are according to the expectations. Ozone depletion is mainly caused by the use of fossil fuels. In this study, the main fossil fuel is petroleum coke, obtained by oil refining. This process causes the emission of hydrocarbons, sulphur and nitrogen oxides, and some particulate material. Specially the sulphur and nitrogen oxides react in the atmosphere and, in properly conditions, causes the ozone depletion (Baird, 2002; U. S. Department of Health and Service, 1960)

Already the profile found to Particulate matter formation indicates that emissions from clinkering are the main contributors to this impact category (47.3%). However, electricity and raw materials extraction also present important contributions, 20 e 16% respectively. In the sequence, we analyzed the impact categories regarding acidification, eutrophication and resource depletion in Table 9 and Figure 14.

Table 9: Absolute values of impact categories regarding acidification, eutrophication and resource depletion to “European Company” through Recipe method.

Impact category	Unit	Total
Terrestrial acidification	kg SO_2 eq	1.99E+00
Freshwater eutrophication	kg P eq	2.89E-02
Marine eutrophication	kg N eq	7.88E-02
Metal depletion	kg Fe eq	1.30E+00
Fossil depletion	kg oil eq	9.11E+01

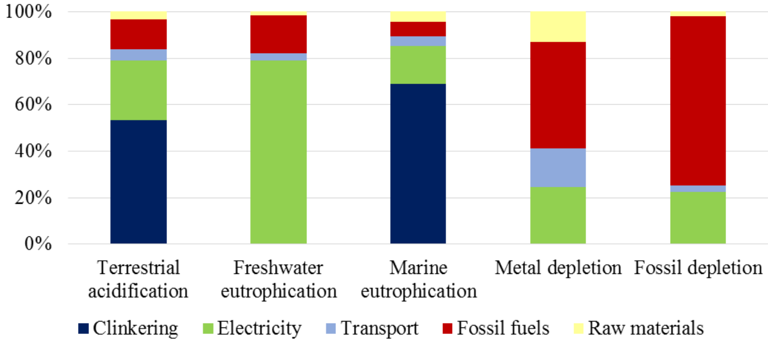

Figure 15: Contribution of each unit of production to impact categories of acidification, eutrophication and resource depletion according to Recipe method.

The impact category Terrestrial acidification can be directly compared to Acidification Potential (CML 2001). The absolute values was similar, just as the contribution profiles.

This similarity is not seen in relation to the impact categories of eutrophication. First, because in CML 2001 method, this impact is considered in terms of Eutrophication Potential and in Recipe method it is divided in Freshwater eutrophication and Marine Eutrophication. In addition, the units of these impact categories are different, making impossible further comparisons. However, the analysis according to Recipe method shows that Freshwater eutrophication is mainly affected by electricity and Marine Eutrophication by clinkering unit of production. Similar division occur to Abiotic Depletion Potential (CML 2001), considered in terms of Metal depletion and Fossil depletion according to Recipe. In both categories, the fossil fuel obtaining presents greatest contribution, although it is more expressive to Fossil Depletion. Electricity also presents significant contribution to both categories, due to the use of fossil fuels to energy generation. The electricity also presents significant contribution to all impact categories of toxicity, discuss in Table 10 and Figure 16.

Table 10: Absolute values to toxicity impact categories to "European Company" according to Recipe.

Impact categories	Unit	Total
Human toxicity	kg 1,4-DB eq	4.16E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	3.26E-02
Freshwater ecotoxicity	kg 1,4-DB eq	5.15E-01
Marine ecotoxicity	kg 1,4-DB eq	6.01E-01

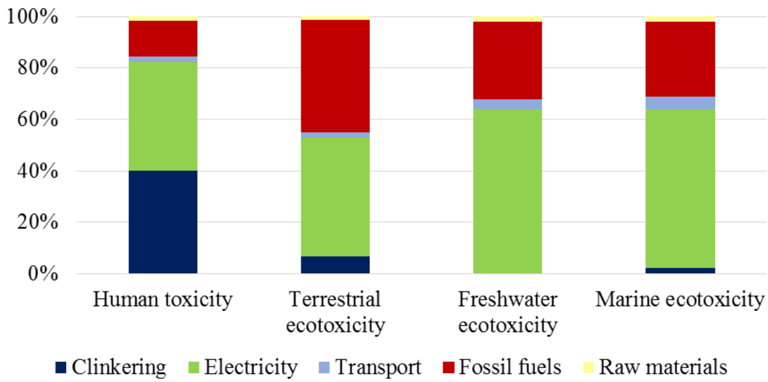

Figure 16: Contribution of each unit of production to the toxicity impact categories according to Recipe.

Atmospheric emissions from clinkering contributes to Human Toxicity almost in the same scale of electricity. The same do not occur to other toxicity impact categories, where the main contributor are the electricity and the fossil fuel obtaining.

In general, therefore, seems that despite the differences in the absolute values through the two impact assessment methods, there is no change in the general conclusions, that is, clinkering, electricity and fossil fuel obtaining, in this order, are the main contributor to the impact categories analyzed.

4.3. Life Cycle Assessment Applied to the Brazilian Cement Production[4]

4.3.1. Introduction

The cement production in Brazil started in the early XIX century, by the inauguration of the Brazilian Cement Company in 1926, but only in 1933 the local production exceeded the amount imported from European market. Since then, as cement is an indispensable industrial product for economic development, the production of cement in Brazil follows the ups and downs of local and global economy. The last expressive growth period began in 2004, and year after year production records have been achieved (SNIC, 2011; Uwasu et al., 2014). Brazil occupies the 5th position of world cement production, behind China (the largest cement producer in the world with 2,438 million tonnes in 2014), India, the European Union and USA, as shown in Figure 17 (Cembureau, 2014).

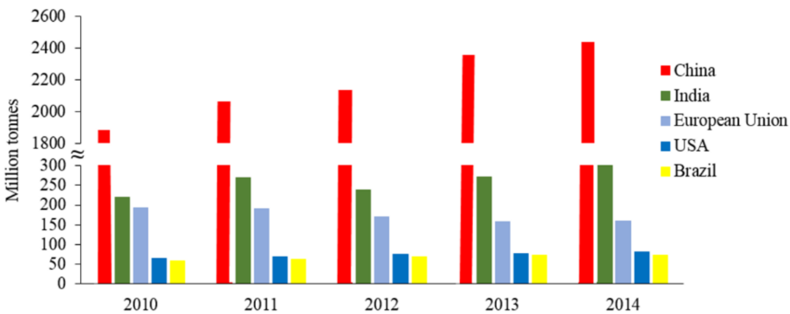

Figure 17: World largest cement producers(Cembureau, 2014).

However, this huge production comes with an environmental concern associated. Figure 18 shows a diagram of the cement manufacturing process, which involves large amounts of raw materials and intensive use of energy (Aranda Usón et al., 2013). In fact, each tonne of Portland Cement needs approximately 1.4 tonne of limestone and minor quantities of other materials such as clay, sand and iron ore, totalizing, overall, 1.6 tonne of raw materials (Huntzinger and Eatmon,

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[4] Submitted to *Resources, Conservation and Recycling*.

2009). Those materials are properly mixed, and submitted to a calcination process, being heated up to 1450°C to form a cement precursor, the clinker. Finally, the clinker is mixed to gypsum and, after a grinding process, the product is known as Portland cement.

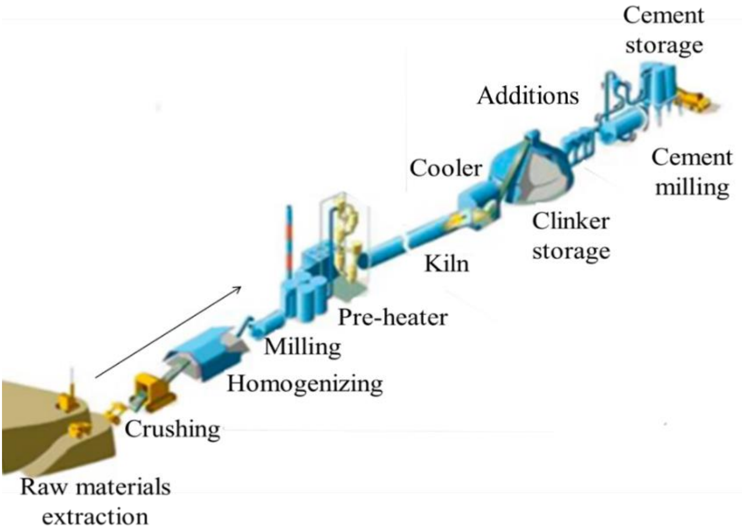

Figure 18: Cement manufacturing processing steps. Adapted (Aranda Usón et al., 2013).

The energy consumption in this process is also impressive: each tonne of clinker requires 2.9 – 3.3 GJ of energy, considering best available techniques. In older facilities the energy demand can reach more than 6.0 GJ/ton of clinker (Ali et al., 2011; Pacheco-Torgal et al., 2014). The most common fuels used in cement industry are coal, fuel oil, petroleum coke, natural gas, biomass and waste fuels (Madlool et al., 2011; Pacheco-Torgal et al., 2014). In this context, a number of fuels can be combined to reach the required temperature inside the cement kilns. However, choosing the adequate fuel(s) to each process depends on the type of cement produced, the factory technology and available options according to technical and economic issues. The use of waste fuels is called co-processing and has been practiced worldwide.

According to the European Cement Association, (CEMBUREAU, 2009), co-processing represents a win/win/win situation: the cement industry wins due to a cost-effective substitution of natural resources thereby improving the competitiveness. The society wins due to a long term and sound solution for the treatment of different types of wastes; and the environment wins due to important saving of natural resources.

Nevertheless, due to the huge use of raw materials and fossil fuels, and chemical reactions that occur in the kilns, the cement industry is responsible for a number of environmental impacts. Global warming can be considered the main impact, since more than 5% of global anthropogenic CO2 is generated in cement production, but there are also substantial emissions of SO2, NOx and other pollutants that must be carefully evaluated (Benhelal et al., 2013; Feiz et al., 2014a; Vatopoulos and Tzimas, 2012; Zhang et al., 2014).

In this context, LCA is an environmental management tool that allows investigates environmental impacts of products and processes. Through LCA it is possible to find hotspots of production and purpose mitigation regulations. Several studies have documented the cement production and co-processing effects in countries as China (Chen et al., 2014a), India (Research, 2013), Mexico (Fry, 2013b; Güereca et al., 2015) and regions as European Union and Latin America (Genon and Brizio, 2008; Harder, 2007; Josa et al., 2007, 2004; Kikuchi and Gerardo, 2009; Rovira et al., 2014; Stafford et al., 2015), mostly using LCA approach.

Brazil, as one of the largest cement producers in the world, counts on statistical data from ABCP (Brazilian Association of Portland Cement), SNIC (National Trade Union of the Cement Industry) and few scientific studies regarding co-processing, mostly focused in the use of tires or biomass(Freitas and Nóbrega, 2014; Lagarinhos and Tenório, 2008; Rocha et al., 2011; M. a Sellitto et al., 2013).

According to ABCP and SNIC, there are 37 industrial facilities authorized to use wastes as raw materials or fuels in Brazil. In 2013, those factories co-processed 1.245.000 tonnes of wastes, including 286.000 tonnes of tires and 199.200 tonnes of biomass, reaching thermal substitution rates of 9%. In this regard, the FICEM (Interamerican Federation of Cement) states that the Brazilian cement industry is one of the most environmental friendly in the world. Nevertheless, countries such as Norway, Germany, Austria and The Netherlands reached replacement ratios much more expressive (higher than 60%)(Aranda Usón et al., 2013).

In this scenario, the present study aims to assess the environmental performance of Brazilian cement industry through LCA. To this purpose, we first describe the details of LCA methodology and data mining, followed by impact assessment results and discussion.

4.3.2. Methodology

LCA is a methodological approach focused on environmental aspects and impacts of services, products or processes. It is guided by ISO 14040 and ISO 14044 (ISO, 2006a, 2006b). According to those standards, LCA studies comprise four stages: goal and scope definition, inventory analysis, impact assessment and interpretation. In this paper, the goal is investigating environmental impacts from the Brazilian cement production, limiting it to extraction of required raw materials and fuels, electricity usage and emissions from the industrial process. Usage and final disposition of cement as waste will not be considered due to methodological aspects. Thus, this is a cradle-to-gate LCA study (Finnveden et al., 2009; ISO, 2006a, 2006b). In other words, the boundaries of the studied system are the extraction/production of supplies and the emissions associated to Portland cement production, as shown in Figure 19.

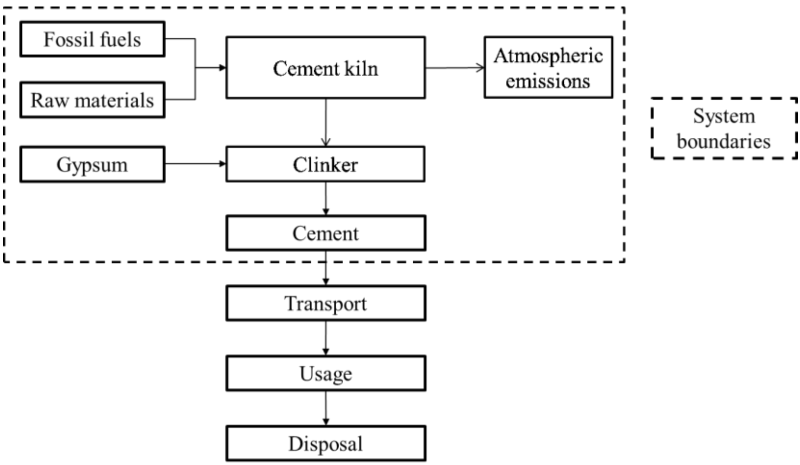

Figure 19: System boundaries, including extraction and production of supplies, but excluding transport, usage and final disposal of cement.

The life cycle inventory can be divided into background and foreground system. In this case, inventory data corresponding to the background system, namely extraction of raw materials, fossil fuels and electricity production, were taken from the Ecoinvent database (Inventories, 2010), including materials and infrastructure requirements to develop the production steps. Foreground system was based on public data regarding national cement production. We considered inputs of limestone, clay, sand, iron oxide and gypsum as raw materials as recommended by ABCP (ABCP, 2002), in estimated quantities according to Huntzinger & Eatmon (Huntzinger and Eatmon, 2009). Electricity consumption is the average for Latin America (FICEM, 2013) and the use of fossil fuels was calculated based on petroleum coke heating value, since it is the main fuel used by Brazilian cement industry (SNIC et al., 2012). Atmospheric emissions from the kiln are based on maximum level allowed by national regulations, CONAMA 436/2011, CONAMA 264/1999 and CONAMA 316/2002 (CONAMA, 1999; 2002; 2011) . The outputs considered are emissions from the mills and kiln. Figure 20 details inputs and outputs of this process, as well as describes foreground and background system. The functional unit is one tonne of Portland cement.

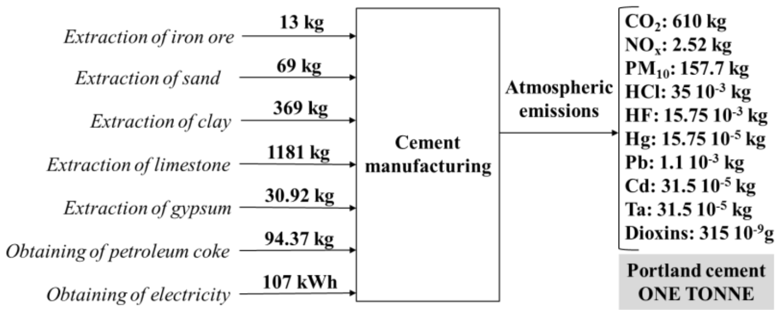

Figure 20: Inputs and outputs considered in this study. Background system in italic; foreground system bolded.

The impact assessment methodology was conducted using the Recipe method, version 1.06 (Goedkoop et al., 2012). The impact categories correspond to three general classes, as described in Table 11. The inputs and outputs presented in Figure 4 to the system of cement production were divided in four steps, as follows: raw materials extraction, fossil fuel obtaining/use, electricity obtaining/consumption and clinkering. Thus, we relate each one of these steps to the impact categories analyzed. All calculations have been performed with the LCA software SimaPro (Pré, 2014).

Table 11: Classification of impact categories assessed.

Atmospheric impacts	Resource depletion	Toxicity
Climate change	Terrestrial acidification	Human toxicity
Ozone depletion	Freshwater eutrophication	Terrestrial ecotoxicity
Photochemical oxidant formation	Marine eutrophication	Freshwater ecotoxicity
Particulate matter formation	Metal depletion	Marine ecotoxicity
	Fossil depletion	

4.3.3. Results and Discussion

Table 12 presents LCIA for atmospheric impacts categories. Figure 21 shows the contribution of each production step to these impacts.

Table 12: LCIA of atmospheric impacts of Brazilian cement production according to Recipe.

Impact category	Unit	Total
Climate change	kg CO_2 eq	6.87E+02
Ozone depletion	kg CFC-11 eq	5.07E-05
Photochemical oxidant formation	kg NMVOC	2.99E+00
Particulate matter formation	kg PM_{10} eq	8.36E-01

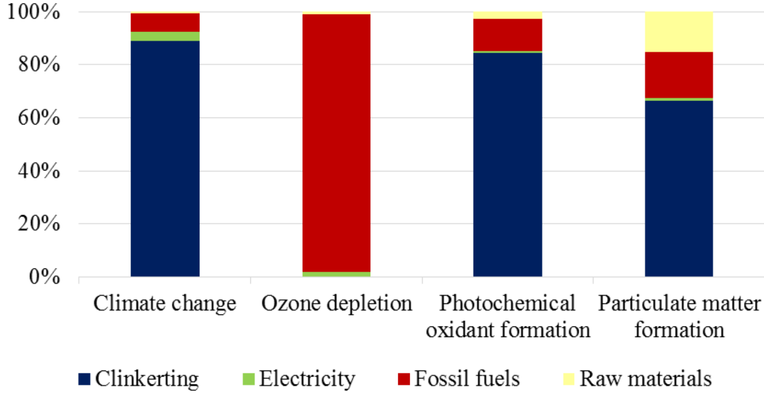

Figure 21: Contribution of each production step to atmospheric impacts.

The first impact, climate change, which can be also understood as global warming potential, is probably the most studied impact regarding cement production (Benhelal et al., 2013; Chen et al., 2014b; Feiz et al., 2014a; Vatopoulos and Tzimas, 2012; WBCSD, 2009c; Zhang et al., 2014), since the atmospheric emissions from the clinkering are the main contributor to this category (in this study, 89%, approximately). However, electricity and fossil fuels production also present important contributions. Those results seem to be consistent with the data from Chen et al., which analyzed the cement production in China and found emissions between 690 and 1.000 kg of CO2 equivalent. They also stated that around 81% were from direct emissions from the kiln (Chen et al., 2014a). Other studies arrived to similar values (Güereca et al., 2015; Huntzinger and Eatmon, 2009; Valderrama et al., 2012), what was expected since the characterization factors are quite similar. In those cases, calcination of limestone corresponded to the main source of CO2 in the cement production (around 60%). However, it is important to highlight that the value obtained in this work, 687 kg of CO2 equivalent, is relatively low for the cement industry, and it was reached due to the use of other fuels than petroleum coke and to the new industrial facilities, which employ the latest technology with the lowest specific energy demand (IPCC, 2007; Stafford et al., 2015).

The ozone depletion, also called "ozone hole", is mainly affected by fossil fuel production. Petroleum coke, the fossil fuel used in Brazilian cement production, is the result of the decomposition of heavy petroleum. This process causes emissions of hydrocarbons, carbon monoxide, particulate matter, sulfur and nitrogen oxides. Especially sulfur and nitrogen oxides react in stratosphere, and, in appropriate conditions, contribute to the ozone layer depletion (Baird, 2002; U. S. Department of Health and Service, 1960).

Despite the benefits of stratosphere ozone layer, the tropospheric ozone is extremely dangerous to human health because it can inflame airways and damage lungs (Goedkoop et al., 2012). However, ozone is not directly emitted into the atmosphere, but it is formed as a result of photochemical reactions of NOx and Non Methane Volatile Organic Compounds (NMVOCs), which is also the measurement unit of the impact category of photochemical oxidants formation (Goedkoop et al., 2012). Thus, the clinkering and its atmospheric emissions from the process and the fossil fuels obtaining are the main contributor to this impact category.

The particulate matter formation is mainly affected by the emissions from the process. This result was expected, since the emissions from the mills were analyzed jointly with the emissions from the cement kilns.

Table 13 presents LCIA for the second general classes of impact categories – resource depletion. The contributions of each production step to these impacts are shown in Figure 22.

Table 13: LCIA of resource depletion of Brazilian cement production according to Recipe.

Impact category	Unit	Total
Terrestrial acidification	kg SO_2 eq	2.03E+00
Freshwater eutrophication	kg P eq	1.13E-02
Marine eutrophication	kg N eq	1.13E-01
Metal depletion	kg Fe eq	1.16E+01
Fossil depletion	kg oil eq	1.40E+02

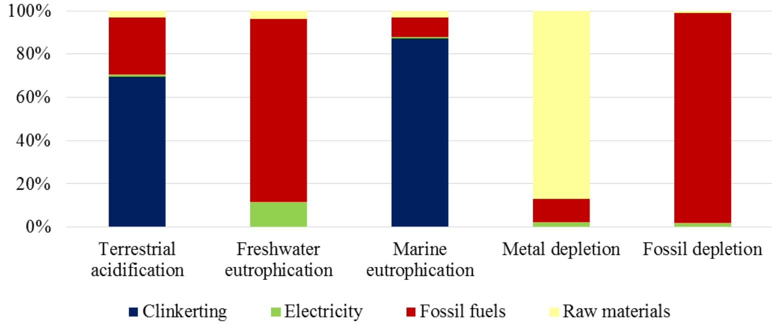

Figure 22: Contribution of each production step to resource depletion impacts.

The main cause of acidification is SOx and NOx emissions, assessed in terms of SO2 equivalent (2.03 kg of SO2 per tonne of cement). Josa et al. (Josa et al., 2007) analyzed a number of LCA studies of cement industries in Europe, and stated that, for Portland Cement, the total acidification ranges from 1.1 to 3.4 g of per kilogram of cement.

Eutrophication impacts are consequence of, but not only, emission of nitrogen oxides. This emission, in cement manufacture, occurs mostly due to the type of fuel used in the cement kiln (Josa et al., 2007). Other studies (Chen et al., 2010; Güereca et al., 2015; Josa et al., 2007) show that the atmospheric emissions from the clinkering process are the main contributor to eutrophication impact; however, due to methodological aspects, we do not recommend direct comparison.

The same concern is regarding to metal and fossil depletion. Chen et al. (Chen et al., 2010) stated that the clinker production is the main responsible for “abiotic depletion”, measured in terms of Sb equivalent, followed by raw material preparation. However, the impact category “abiotic depletion” considers simultaneously the use of fossil fuels in the cement kiln and the raw materials obtaining. In this study, the raw materials obtaining is considered in metal depletion category, while fossil fuels extraction is considered as fossil depletion. In this way, obtained results were expected: raw materials expressively contributing to metal depletion and fossil fuels contributing to fossil depletion.

Table 14 presents the LCIA of toxicity impacts. The contributions of each production step to these impacts are shown in Figure 23.

Table 14: LCIA of toxicity impacts of Brazilian cement production according to Recipe.

Impact category	Unit	Total
Human toxicity	kg 1,4-DB eq	1.30E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	5.31E-02
Freshwater ecotoxicity	kg 1,4-DB eq	3.56E-01
Marine ecotoxicity	kg 1,4-DB eq	5.08E-01

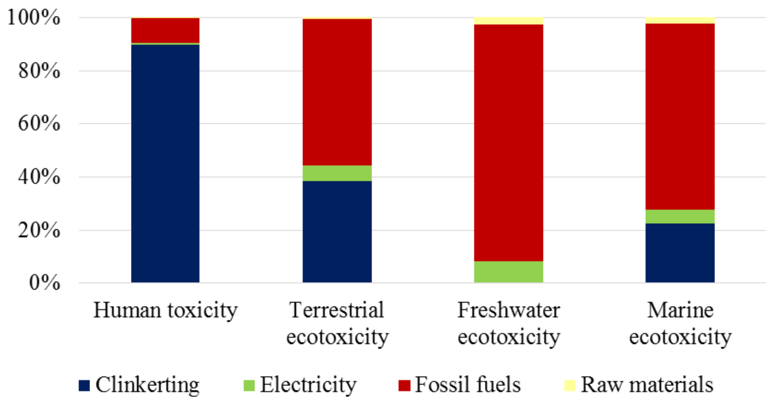

Figure 23: Contribution of each production step to toxicity impacts.

According to Recipe, all toxicity impacts are measured as 1,4-dichlorobenzene equivalents; however, issues relating to toxicity generate much debate. Human and ecotoxicological impacts are troublesome impact categories for several political as well as scientific reasons. The lack of inventory data and the models used and related data lead to a poor or no agreement regarding toxicity impacts assessment between the LCIA methods(Finnveden et al., 2009; Pizzol et al., 2011).

Even so, with respect to cement production, Fiksel et al. (Fiksel et al., 2011) stated that the use of end-of-life tires in cement kilns can cause minimal benefits in terms of reducing toxicity impacts. To Conesa et al. (Conesa et al., 2008), one of the major hazards in the alternative fuels usage is the heavy metal content. According to them, the emission of higher toxicity metals, such as mercury, do not increase with the increase in tires ratio, but there are higher ratios of nickel and lead. This is important since the main impact in this category is the human toxicity (99.3%), mostly derived from emissions from the kiln (89.6%).

However, in this study, we used the maximum amount allowed by the Brazilian legislation to estimate the emission of pollutants from the cement kiln. Therefore, the total impact values may be different from the values pointed here, especially for human toxicity, terrestrial and marine ecotoxicity. It is also important to mention that toxicity impacts mainly caused from atmospheric emissions from the clinkering can directly affect the surrounding area of the factory, while toxicity impacts from fossil fuels extraction or electricity production occur in other places than the cement factory (Josa et al., 2007).

Since impacts of ozone depletion, freshwater eutrophication, fossil depletion and environmental toxicities are strongly affected by fossil fuels usage, it is possible that, when increasing the use of co-processing techniques, especially replacing fossil fuels, the total values could be reduced.

Developers of Recipe impact assessment method observed that environmental mechanisms such as acidification, eutrophication, photochemical ozone formation, toxicity and other not appreciated in this study, depend on regional conditions and regionally different parameters. They attempted to generalize the models as much as possible to be relevant for all developed countries in temperate regions; however, the validity for all regions or developing countries might be limited (Goedkoop et al., 2012).

A good example is the photochemical oxidant formation, which is much more expressive in summer. As Brazil has in average higher temperatures than Europe, it is expected that this impact modeling should be significantly different in those regions. However, we consider that identifying this lack of data is recognizing the necessity of models based on other economies than developed countries.

4.3.4. Conclusions

In this study, we assessed the environmental performance of the cement industry in Brazil through LCA methodology. To this purpose, we used public data to the foreground system and Ecoinvent database to the background system. It means that not all production activities are properly represented, although it can be a first step to better understand environmental issues to Brazilian industries. The impact assessment conducted based on Recipe method showed that the emissions of CO2 seems to be aligned to other studies, and the amounts estimated here are even lower than those obtained in other countries. The main contributor to the impact category of climate change is, as expected, the emissions from the process. Those emissions are also the main contribution to photochemical oxidants formation, particulate matter formation, acidification, marine eutrophication and human toxicity. Except for metal depletion, mainly caused by the extraction of raw materials, all other impact categories are majorly affected by fossil fuel obtaining.

4.4. Life Cycle Assessment of the Production of Cement: A Brazilian Case Study[5]

4.4.1. Introduction

Cement is a common building material widely used as a component in mortar, grout and concrete, which is considered the most consumed material worldwide (WBCSD, 2009). The evolution of cement production is linked to the economic activity and to the levels of industrialization and infrastructure development. The intensity of cement demand is decreasing in developed countries and increasing in many developing countries (Pacheco-Torgal et al., 2014). The cement production in the five major emerging national economies, named BRICS (Brazil, Russian Federation, India, China and South Africa), is presented in Table 15, which clearly represents this trend.

Table 15: Cement production (million t) for BRICS. Adapted (Cembureau, 2014).

Country	2001	2006	2011	2012	2013	2014
Brazil	39.4	41.4	63.0	68.0	71.9	72.0[p]
Russian Federation	28.7	54.7	56.1	53.0	55.6	68.4[p]
India	102.9	159.0	270.0	239.0	272.0	300.0[p]
China	661.0	1236.8	2063.2	2137.0	2359.0	2438.0[e]
South Africa	8.4	13.1	11.2	13.8	14.9	13.8[e]

[p] Preliminary; [e] Estimate

[5] Submitted to *Journal of Cleaner Production*.

The Brazilian market increased the cement production from 39.4 Mt in 2001 to 72.0 Mt in 2014. Certainly, this huge production comes with associated environmental concerns. Cement production requires large amounts of raw materials and energy. In fact, 1 t of ordinary Portland cement can consume more than 1.5 t of raw materials and 2.93 to 6.28 GJ of thermal energy, besides 65 to 141 kWh of electrical energy (Huntzinger & Eatmon, 2009; Madlool et al., 2011; Valderrama et al., 2012).

Cement production involves the mining of raw materials, such as limestone, clay, and sand. A number of industries also use selected wastes as additions or partial substitutes of raw materials. Those materials are ground and mixed before firing at 1450°C (Pacheco-Torgal et al., 2014). The result is the clinker, which is mixed with other materials, especially gypsum, originating the cement.

Cement kilns use different energy sources to reach the high temperatures necessary to form the clinker. Many fuels can be used: fossil fuels, as mineral coal, fuel oil, petroleum coke, natural gas and diesel; and alternative fuels, as waste or biomass (Madlool et al., 2011). Due to the significant amounts of cement produced and the raw materials and energy required, the cement industry becomes a source of environmental concerns. This is especially due to high emissions of CO2, originated by the use of fossil fuels, as well as the decarbonation of limestone in the clinker production (Ali et al., 2011)

One way to decrease CO2 emissions is diminishing the portion of clinker in the cement. The amount of clinker needed to produce a given amount of cement can be reduced by the use of supplementary cementitious materials such as coal fly ash, slag, and natural pozzolans, such as rice husk ash and volcanic ashes (Huntzinger & Eatmon, 2009).

Thus, the final composition of cement can vary, originating different product standards, which are indicated to distinct uses. Table 16 describes the five Portland cement types currently standardized and available in Brazil.

Table 16: Cement type, clinker content and application.

Cement Type	Clinker Content (wt.%)	Application
I Ordinary Portland	0.95	General construction (buildings, bridges, pavements)
II Portland Composite	0.65-0.94	Structures exposed to soil or water containing sulfate ions
III Blast Furnace	0.05-0.64	Rapid construction, cold weather concreting
IV Pozzolanic	0.45-0.89	Massive structures such as dams
V Composite	0.20-0.64	Structures exposed to high levels of sulfate ions

Adapted (Ecofys et al., 2009; SNIC et al., 2012; Thomas & Jennings, n.d.)

CP II and IV are environmentally friendlier than CP I due to less clinker content. However, the production of cements types II and IV depends on availability of supplementary cementitious materials. According to the National Trade Union of the Cement Industry (SNIC) around 60% cement produced in Brazil is type II and 14% is type IV (SNIC, 2013b). The increasing use of additions has represented one of the most effective measures to control and reduce CO2 emissions from the industry. The country also has a modern and efficient production base with facilities that operate with low energy consumption, and burning waste through co-processing has increased since 2000's (Kihara & Visedo, 2014). In 2013, 37 facilities were authorized to employ co-processing and the thermal substitution was 9% (ABCP, 2013). By contrast, countries such as Norway, Germany, Austria and The Netherlands reached replacement ratios much more expressive (higher than 60%) (Aranda Usón et al., 2013).

Nevertheless, it is a challenging task to state how a certain industry operates from the environment perspective, particularly in the cement production in Brazil. Environment-related scientific studies regarding cement industry in this country are rare and mostly focused on the use of biomass or tires as alternative fuels (Lagarinhos & Tenório, 2008; Lamas et al., 2013; Sellitto et al., 2013).

In this context, we aim to evaluate the environmental impacts of one Brazilian cement plant that produces CP II and CP IV through life cycle assessment (LCA). Additional information cannot be provided due to confidentiality agreement.This methodology allows identifying environmental hotspots in the production process and making comparisons to other similar production scenarios that were also evaluated by LCA.

4.4.2. Methodology

Life cycle assessment is based on environmental aspects and impacts of services, products or processes. It is guided by ISO 14040 and ISO 14044 (ISO, 2006a, 2006b). According to those standards, an LCA study must comprise four stages: goal and scope definition, inventory analysis, impact assessment and interpretation. In this study, the goal is investigating environmental impacts based on data generated by a production unit of cement, limiting it to extraction of required raw materials and fuels, transportation of these inputs, electricity usage and emissions from the industrial process. Consumption and final disposition of cement as waste were not taken in account due to methodological aspects. Thus, the extraction/production of supplies and the emissions associated to Portland cement production are within the boundaries of the studied system, as shown in Figure 24. In this case, foreground systems correspond to processes whose actions can be directly measured (primary data); background systems are related to processes whose actions cannot be directly taken. In the latter systems, external secondary data are used instead. The functional unit is 1 tonne of Portland cement produced by the plant.

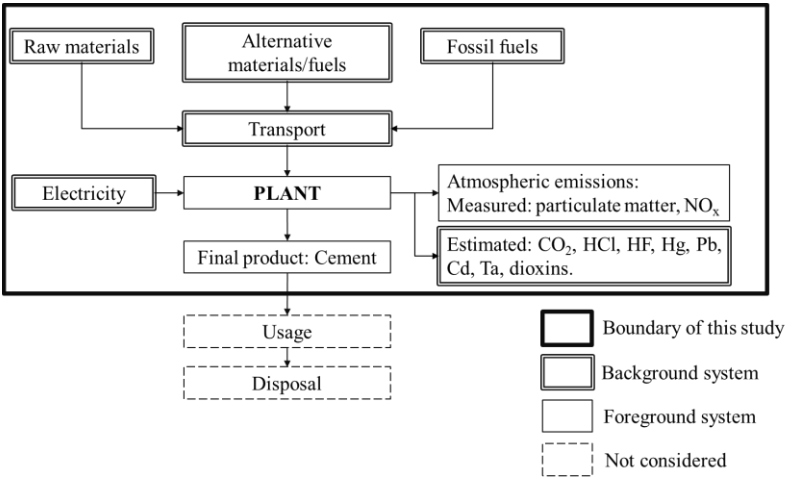

Figure 24: System boundaries of the LCA of a cement plant in Brazil.

The inventory was based on primary data in the current year. Unavailable data were collected from statistics of average Brazilian cement production or national regulations. Inventory data corresponding to the background system were taken from the Ecoinvent database (Ecoinvent, 2010). Main raw materials are limestone, sand and clinker (acquired in part from an external source). Minor contents of fly ash, iron ore, slag, among others, and chemical additives are also used. Fossil fuels are diesel, bituminous coal and petroleum coke. Table 17 shows the source of data used in this study.

Table 17: Sources of inventory data of a cement plant in Brazil.

Inputs	Type	Source
Raw materials		
Sand Limestone Clinker Minor raw materials Chemical additives	Primary data	Plant consumption
Energy		
Electricity Fossil fuels	Primary data	Plant consumption
Transportation		
Oceanic transportation Road transportation	Primary data	Plant information
Clinkering		
Particulate matter NO_x	Primary data	Plant information
CO_2	Secondary data	Brazilian average (MMA, n.d.; Cimento.org, 2012)
HCl HF Hg Pb Cd Ta Dioxins	Secondary data	Brazilian regulation (CONAMA, 1999)

The impact assessment was conducted based on ReCiPe hierarchist v. 1.06. The method has been given the name ReCiPe as it provides a “recipe” to calculate life cycle impact category indicators. The acronym also represents the initials of the institutes that were the main contributors to this method. (Goedkoop et al., 2012). The impact categories correspond to three general classes: atmospheric, resource depletion and toxicity. Atmospheric impacts are climate change (CC), ozone depletion (OD), photochemical oxidant formation (POF) and particulate matter formation (PMF). Resource depletion impacts are terrestrial acidification (TA), freshwater and marine eutrophication (FE and ME, respectively), metal and fossil depletion (MRD and FD, respectively). Toxicity impacts are human toxicity (HT), terrestrial, freshwater and marine ecotoxicity (HT, TET, FET and MET, respectively). The inputs and outputs, presented in Figure 1, were divided in five production units, as follows: raw materials, fossil fuels, electricity, transportation and clinkering.

All processes considered in each production unit are described in Table 18. Through LCA methodology, each one of these steps is related to the impact categories analyzed (detailed in Table 5). All calculations have been performed with the LCA software SimaPro 8.0.3.14 (Prè, 2014).

Table 18: Processes considered in each production unit of a cement plant in Brazil.

Production unit	Processes considered
Raw materials	Limestone and sand extraction. Clinker and diethylene glycol production, including the inputs, outputs, processes and capital goods required.
Fossil fuels	Diesel, petroleum coke and bituminous coal obtaining, including inputs, outputs, processes and capital goods requirement.
Electricity	Electricity used in administrative buildings, mills and other equipment, in accordance with Brazilian production and distribution (Inventories, 2010)
Transportation	Road transportation and transoceanic freight ship of raw materials, alternative materials and fossil fuels.
Clinkering	Particulate matter, NO_x, CO_2, HCl, HF, Hg, Pb, Cd, Ta and dioxins emitted by the kiln during clinker production.

Due to the lack of LCA studies of cement industry using ReCiPe method, a direct comparison of results is not possible. In this regard, an analysis of generic Portland cement production described in Ecoinvent database was also performed. This alternative, called "standard scenario", includes raw materials extraction, fossil fuels, electricity, transportation and clinkering.

4.4.3. Results and Discussion

Table 19 presents the absolute values of each atmospheric impact category, according to ReCiPe metrics to both scenarios. Figure 25 shows the contribution of each production step to atmospheric impact categories.

Table 19: Total values for atmospheric impacts (1 t of Portland cement).

	Impact category	Unit	This study	Standard scenario
CC	Climate change	kg CO_2 eq	2.16E+03	1.73E+03
OD	Ozone depletion	kg CFC-11 eq	2.54E-04	3.97E-06
POF	Photochemical oxidant formation	kg NMVOC eq	1.18E+01	3.98E+00
PMF	Particulate matter formation	kg PM_{10} eq	3.32E+00	2.16E+00

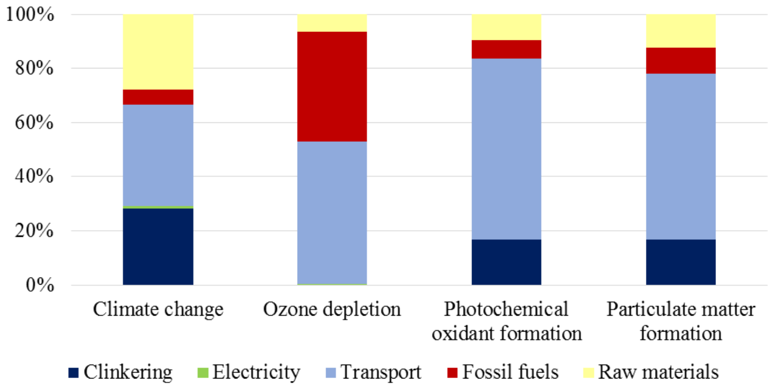

Figure 25: Contribution of each production unit to atmospheric impacts.

CC is probably the most studied impact regarding cement production (Ammenberg et al., 2014; Benhelal et al., 2013; Chen et al., 2014a; Feiz et al., 2014a, 2014b; Uwasu et al., 2014; Vatopoulos and Tzimas, 2012; Zhang et al., 2014) and it is measured in terms of carbon dioxide equivalent (kg CO2 eq). In fact, 1 kg CO2 is equal to 1 kg CO2 equivalent, while for other compounds, for example, methane, 1 kg can be equal to 25 kg of CO2 equivalent. However, due to the large amounts of CO2 emissions inherent to clinker production, these emissions are the main contributors to climate change in this case. CC world average of dioxide emitted from cement production is about 0.8 to 1.0 t of carbon dioxide per t of Portland cement (Feiz et al., 2014a; Hu et al., 2014; Pacheco-Torgal et al., 2014; M. a Sellitto et al., 2013). Based on previous studies, it was expected that emissions from the cement kiln would be the main contributor CC impacts (Feiz et al., 2014a; Huntzinger & Eatmon, 2009). However, in addition to these emissions, there are also emissions associated to other production units that increase the atmospheric impacts. Emissions from the kiln are responsible only for ~30% of the total value reached in this study (2.16E+03 kg of CO2 equivalent, against 1.79E+03 in the standard scenario), as discussed in the following paragraph.

The transportation was the main contributor to this impact category. It occurs because, in Brazil, road transportation is the most representative. The country counts on 1.7 million km of roads, against less than 29.000 km of railways and 22.000 km of economically navigable waterway network (MTE, 2014a, 2014b, 2014c). Due to this, 95% of transportation operations are done by truck and, specifically in this case, distances can vary from 25 km to more than 1000 km. Besides the well-known restraints associated to road transportation (moderated velocity, high maintenance costs and limitations of volume and weight for the loads), 100 t of material transported for 1 km by truck is responsible for the emission of 13.7 kg of CO2 equivalent, besides the consumption of 5.27 kg of oil equivalent (Inventories, 2010; MTE, 2014a).

It is important to highlight that road transportation of acquired clinker is the main contributor to the transportation step. Nevertheless, this condition is not usual in cement industries in Brazil. This is the reason why the extraction of raw materials had an expressive contribution. The amount of imported clinker was considered “raw material", affecting the influence of this step on the analyzed impact categories.

These particularities certainly affected the absolute value found for this and to other impact categories. Moreover, it is important to highlight that the emission of CO2 from the cement kiln was estimated from the average data for the Brazilian cement industry (MMA, n.d.; Cimento.org, 2012). In addition, other compounds were estimated from maximum values allowed by national regulations, eventually causing overestimations.

OD occurs if the rate of ozone destruction is increased due to anthropogenic emissions of recalcitrant chemicals that contain chlorine or bromine atoms (Goedkoop et al., 2012). The measure to OD is CFC-11 equivalent, also known as trichlorofluoromethane or Freon 11. It is mainly affect by chlorinated or brominated hydrocarbons emitted mainly along the production of fossil fuels. Due to this, disregarding transportation, this step is the main contributor to this impact category (Baird, 2002; Goedkoop et al., 2012). However, in many studies, the absolute values of this impact category were considered very low in comparison to other impact categories, thus, it has not been analyzed so often (Feraldi et al., 2012; Hu et al., 2014). In this study and in the standard scenario, the values found were 2.54E-04 and 3.97E-06 kg of CFC-11 eq, respectively. This difference can be explained by the influence of transportation and the different fuels mix considered in this study and in the standard scenario.

POF is measured in non-methane volatile organic compounds equivalent (NMVOC eq). Comparably to OD, some studies did not consider POF. The standard scenario reached 3.98 kg of NMVOC equivalent per t of cement, against 11.8 kg of NMVOC found in this study. Again, the influence of transportation is evident and corresponds to the main cause of the difference. Excluding this step, POF is mainly affect by atmospheric emissions from clinkering and raw materials. In transportation, the contribution regarding the acquired clinker, considered as raw material, cannot be neglected.

The last category of atmospheric impacts, PMF, is measured in terms of particulate matter 10 (PM-10), a standardized size of particles of 10 μm or less. In this study, we found 3.23E+00 kg of PM-10 eq, while standard scenario points to 2.16E+00 PM-10 eq. The similarity between these absolute values can be explained due to accuracy in particulate matter measurements in both scenarios. A similar scenario to that found to POF is evident: atmospheric emissions from the clinkering and the fossil fuels production unit are major contributors to these aspects of evaluation.

Results for resource depletion impacts are presented in Table 20 and Figure 26.

Table 20: Total values for resource depletion impacts (1 t of Portland cement).

Impact category		Unit	This study	Standard scenario
TA	Terrestrial acidification	kg SO_2 eq	7.86E+00	6.31E+00
FE	Freshwater eutrophication	kg P eq	1.38E-01	5.51E-06
ME	Marine eutrophication	kg N eq	4.16E-01	1.39E-01
MD	Metal depletion	kg Fe eq	5.27E+01	-
FD	Fossil depletion	kg oil eq	7.36E+02	1.25E+02

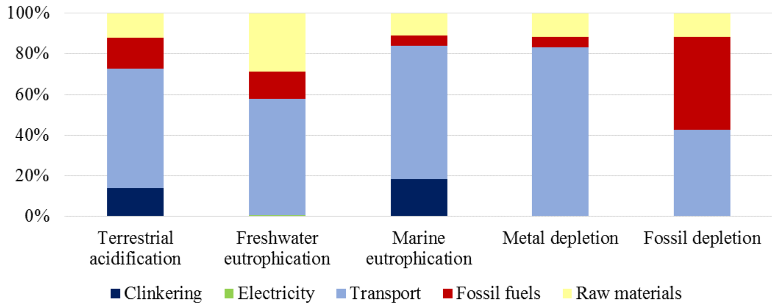

Figure 26: Contribution of each production unit to resource depletion impacts.

Resource depletion impact categories also cannot be compared to other studies due to methodological issues (most studies regarding cement industry uses CML 2001 impact assessment method, which uses different metrics). Even the comparison between this study and the standard scenario must be carefully evaluated, because the methodologies for assess environmental impacts regarding resource depletion still are under development (Bueno et al., 2015; Finnveden et al., 2009; Huppes and Oers, 2011).

For TA, fossil fuels obtaining is the main contributor after transportation, similarly to all other resource depletion impacts. In this study, we found 7.86E+00 kg of SO2 equivalent, against 6.31+00 for the standard scenario, which are values in the same order of magnitude. Atmospheric emissions from the clinkering and raw materials extraction/obtaining presented similar contribution (around 13%, each).

Freshwater and marine eutrophication are measured in terms of phosphorous and nitrogen equivalent, respectively. These categories presented different profiles: if transportation is not considered, FE is mostly affected by raw materials extraction/obtaining and ME is mostly affected by atmospheric emissions from the clinkering. It occurs because FE is dependent from phosphorous compounds, which emissions are, according to the database, significant in the production of some chemical additives considered (Ecoinvent, 2010). In fact, the use of additives is the major cause of the difference between the results found in this study to the standard scenario. Besides this, to FE, there is a huge difference between absolute values found in this study (1.38E-01 kg of P eq) and the standard scenario (5.51E-06 kg of P eq). This occurs because the standard scenario considers only the use of fossil fuels, and does not take into account its obtaining (Ecoinvent, 2010).

In contrast, ME is affected by nitrogen compounds, which result mostly from the oxidation of molecular nitrogen present in combustion air (thermal NOx) and the oxidation of nitrogen compounds in fuel (fuel NOx) (Neuffer & Laney, 2007), explaining the similarity in the results of this study and the standard scenario. Raw materials extraction/obtaining causes around 11% of ME.

Metal depletion (MD) reaches 5.27E+01 kg of Fe equivalent in this study. Excluding transportation, fossil fuels obtaining step is the main responsible for fossil depletion (around 45%, according to Figure 4), as expected. The comparison to the standard scenario was not possible for MD because the inputs of raw materials (as limestone, sand, iron) were considered inputs obtained from nature, having no depletion factor associated.

Fossil depletion (FD) is measured in terms of oil equivalent. Comparing to MD, raw materials presented a similar contribution to both depletions. For FD, this study reached 7.36E+02 kg of oil eq, which is 6 times higher than the standard scenario. The difference is due to the influence of transportation that is also considered in the production of the fossil fuels in this study, while the standard scenario only considers its use.

Next, the results for toxicity impacts are presented in Table 21 and Figure 27.

Table 21: Total values for toxicity impacts (1 t of Portland cement).

Impact category		Unit	This study	Standard scenario
HT	Human toxicity	kg 1.4-DB eq	2.69E+02	7.44E+01
TET	Terrestrial ecotoxicity	kg 1.4-DB eq	1.86E-01	1.53E-02
FET	Freshwater ecotoxicity	kg 1.4-DB eq	3.62E+00	9.34E-02
MET	Marine ecotoxicity	kg 1.4-DB eq	3.94E+00	1.86E-01

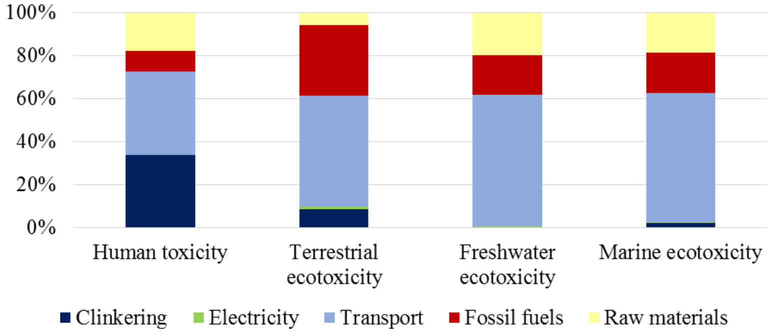

Figure 27: Contribution of each production unit to toxicity impacts.

Toxicity impacts are based on 1,4 dichlorobenzene equivalent, which is the metric adopted by CML 2001 (Institute of Environmental Sciences, 2013). Specifically for human toxicity, Chen et al. (Chen et al., 2010) found 76 1,4-DB equivalent for each t of Portland cement, in comparison to 74.4 for the standard scenario and 269 regarding this study. In this case, it is very important to highlight that part of these impacts are caused by emissions from the cement kiln, which were estimated based on maximum values allowed by national regulations, eventually causing overestimations. Atmospheric emissions from the clinkering are responsible for almost 40% of HT, since we considered the emissions of hazardous pollutants according to the maximum allowed by Brazilian regulations. Still not considering the transportation, the second biggest contributor is the raw materials extraction/obtaining. Again, the acquired clinker has a significant contribution.

Excluding transportation, fossil fuels obtaining presents a large contribution to TET. It occurs especially due to diesel usage, because, according to the database, diesel obtaining causes emissions of hydrocarbons and metals, which are the main contributors to this impact category (Ecoinvent, 2010).

For FET and MET, the difference comparing this study to the standard scenario values is also explained by the influence of transportation unit. Despite this, these categories presented similar profiles, where fossil fuels obtaining and raw material extraction/obtaining have a comparable contribution.

Electricity usage does not present significant contribution to any impact category due to the efficient use of electricity in Brazilian cement plants. In the USA, the average consumption is 146 kWh per t of cement, while world and Brazilian average is 107 kWh (Cimento.org, 2012). The specific plant under analysis reached 81 kWh per t of cement. Besides the low consumption, it is also important to mention that more than 65% of electricity is produced from hydroelectric power plants, which generate less pollutants than other power sources (ANEEL, 2015).

Regarding the replacement of fossil fuels, the Cement Sustainability Initiative states that it can be a good option to reduce fossil fuels usage with lower atmospheric emissions if well controlled (CSI, 2014). The extraction of 100 kg of diesel oil can emit 62.7 kg of CO2 equivalents and contributes to fossil depletion with 127 kg of oil equivalent (Inventories, 2010). However, due to the large use of road transportation in Brazil, the distances between the source of the alternative fuels and the plant must be taken into account.

It is also important considering that an environmental impact is dependent of its origin. Thus, resource depletion or toxicity impacts are associated to regional or local impacts and their effects seems to be diluted as the distance of the source increases. For example, improper disposal of wastes causes a number of diseases affecting mostly the surrounding area. Sometimes differences in sensitivity of the receiving environment can have a stronger influence on the resulting impact than differences in inherent properties of the substance that contribute to the impact. By contrast, climate change or other impacts that occur in global scale does not suffer this influence of the receiver environment (Finnveden et al., 2009).

4.4.4. Conclusions

The LCA methodology was employed to assess environmental impacts from one Brazilian cement plant that produces two types of Portland Cement. The transportation step is the highest contributor to all impact categories analyzed. It occurs because transportation in Brazil is mostly made by road, which is the most polluting means of transportation. However, at the time of this study, the factory was external acquiring part of the clinker from an external source, which is not usual for cement industries. As this condition changed since then, the most impacting steps may be related to fossil fuels obtaining and atmospheric emissions from the clinkering. In this context, the replacement of fossil fuels by alternative fuels can be an option to reach lower environmental impacts. However, the distances from the source of these alternative fuels to the factory must be considered.

4.5. Additional Analysis on Transportation, Energy and Normalization

4.5.1. Sensibility Analysis to Transportation regarding the Scenario "Brazilian Company"

According to the results presented in the section 4.5, we opted for conducting a sensibility analysis to the scenario "Brazilian Company", aiming to identify the influence of the unit of production of transport in the final results. To reach this aim, the distances and modals identified to the Brazilian company were replaced by the distances and modals identified to the European Union company.

The contributions of each unit of production to each impact category are presented in the Figures 28-30. The differences between the values of the scenario "Brazilian Company" and the new scenario created to the sensibility analysis are presented on Table 22.

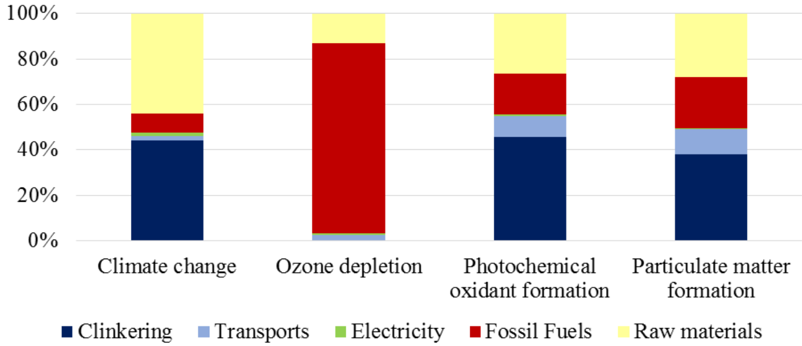

Figure 28: Contribution of each process unit to each atmospheric impacts according the sensibility analysis.

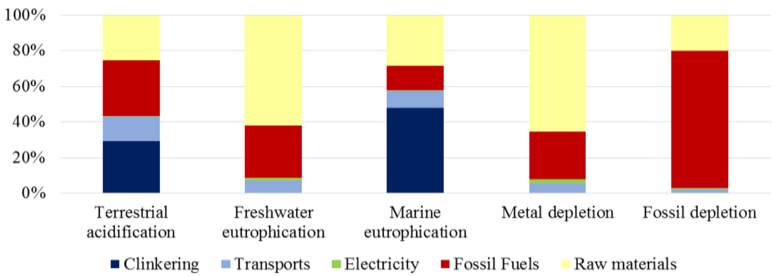

Figure 29: Contribution of each process unit to each resource depletion impacts according the sensibility analysis.

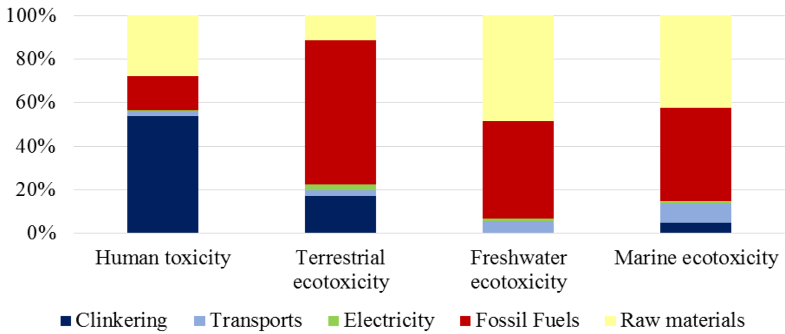

Figure 30: Contribution of each process unit to each toxicity impacts according the sensibility analysis.

Observing Figures 28 to 30, and comparing them to Figures 25 to 27, it is clear the contribution of the transport unit to the analyzed environmental impacts associated with the Brazilian company. Table 22 reinforces this idea, demonstrating the difference between the absolute values found for each impact category according to the stage of production of the Brazilian company and the sensitivity analysis scenario. The climate change is the most discussed impact category, and differences between the two cases, although corresponding to the less affected factor, is still over 35%.

Table 22: Comparison between absolute values of each impact category, considering: (a) Brazilian Company scenario (b) Sensibility Analysis for Brazilian Company scenario.

Impact category	Unit	(a)	(b)	%
Atmospheric impacts				
Climate change	kg CO_2 eq	2.16E+03	1.38E+03	-36.29
Ozone depletion	kg CFC-11 eq	2.54E-04	1.23E-04	-51.58
Photochemical oxidant formation	kg NMVOC	1.18E+01	4.30E+00	-63.50
Particulate matter formation	kg PM_{10} eq	3.32E+00	1.45E+00	-56.19
Resource depletion				
Terrestrial acidification	kg SO_2 eq	7.86E+00	3.76E+00	-52.14
Freshwater eutrophication	kg P eq	1.38E-01	6.38E-02	-53.68
Marine eutrophication	kg N eq	4.16E-01	1.59E-01	-61.68
Metal depletion	kg Fe eq	5.27E+01	9.49E+00	-81.99
Fossil depletion	kg oil eq	7.36E+02	4.33E+02	-41.24
Toxicity				
Human toxicity	kg 1,4-DB eq	2.69E+02	1.68E+02	-37.46
Terrestrial ecotoxicity	kg 1,4-DB eq	1.86E-01	9.28E-02	-50.14
Freshwater ecotoxicity	kg 1,4-DB eq	3.62E+00	1.48E+00	-59.19
Marine ecotoxicity	kg 1,4-DB eq	3.94E+00	1.73E+00	-56.08

4.5.2 Sensibility Analysis according to Electricity Scenarios

The database used in this research, Ecoinvent, contain scenarios of energy production for specific countries for domestic and industrial production. This scenarios feature the energy production from a number of sources, as well as energy importation, according to the situation of energy production in the country. However, these scenarios are based on energy production to the year 2000. Due to this, the Ecoinvent recommends that the utilities data is compiled and used in LCA studies (Ecoinvent, 2010).

Due to this, aiming to compare the proposed scenario by the database and the scenario of energy production to Brazil and European Union to the base-year of this study, 2013, new analysis were developed. Therefore, we considered the composition of energy production to that year, as presented in Table 23.

Table 23: Composition of energy production to Brazil and European Union in 2013.

Source	Production (%)	
	Brazil	European Union
Eolic	5,13	49,6
Hidric	61,56	13,9
Nuclear	1,34	-
Renewable - others	8,90	9,6
Fossil	17,57	8,2
Non renewable cogeneration	-	11,8
Others	5,5	6,9

Adapted from (ANEEL, n.d.; Universal, 2013).

Based on this data, the three scenarios were analyzed again and the results are shown below. Table 24 shows the comparison between the results for " Brazil Estimatives " based on the database energy production model and the "Brazil Estimatives" with the energy balance for the year 2013.

Table 24: Comparison between absolute values of each impact category, considering: (a) energy production of database and (b) energy balance for 2013 for scenario “Brazil Estimatives”.

Impact category	Unit	(a)	(b)	%
Atmospheric impacts				
Climate change	kg CO_2 eq	6.87E+02	6.85E+02	-0.23
Ozone depletion	kg CFC-11 eq	5.07E-05	4.98E-05	-1.60
Photochemical oxidant formation	kg NMVOC	2.99E+00	3.42E+00	14.31
Particulate material formation	kg PM_{10} eq	8.36E-01	8.72E-01	4.24
Resource depletion				
Terrestrial acidification	kg SO_2 eq	2.03E+00	2.18E+00	7.45
Freschwater eutrophication	kg P eq	1.13E-02	1.02E-02	-9.86
Marine eutrophication	kg N eq	1.13E-01	1.15E-01	1.60
Metal depletion	kg Fe eq	1.16E+01	1.16E+01	-0.34
Fossil depletion	kg oil eq	1.40E+02	1.44E+02	2.63
Toxicity				
Human toxicity	kg 1,4-DB eq	1.30E+02	1.30E+02	-0.03
Terrestrial toxicity	kg 1,4-DB eq	5.31E-02	5.04E-02	-4.99
Freshwater toxicity	kg 1,4-DB eq	3.56E-01	3.39E-01	-5.02
Marine toxicity	kg 1,4-DB eq	5.08E-01	4.92E-01	-3.07

According to these numbers, it is possible to observe that "climate change" and "ozone depletion" suffer a reduction of 0.23 and 1.60% when the realistic energy production scenario of 2013 was considered. Besides, impact factors such as photochemical oxidants and particulate materials formation increased 14.31 and 4.24% respectively.

The relatively minor variations estimated can be explained by the fact that Brazilian energy production matrix did not change much between the two years. The energy generated from renewable sources corresponded to 75.59% in 2000, and increased to 79.72% in 2013. In the same years, the burning of fossil fuels contributed with 18.7% and 17.75% in 2000 and 2013, respectively(Data Portal, 2016).

Impacts like "terrestrial acidification", "marine eutrophication" and "fossil depletion" increased 7.45, 1.60 and 2.43% in comparison to the data from the standard scenario of the database. However, "freshwater eutrophication" and "metal depletion" suffer reductions of 9.86 and 0.34%, respectively.

Also, reductions on all toxicity impact categories were observed, but not very expressive. For example, the "human toxicity" parameter changed only -0.03%, while reductions on the "marine ecotoxicity", "terrestrial ecotoxicity" and "freshwater ecotoxicity" factors were 3.07%, 4.99%, and 5.02%, respectively.

A similar tendency was found when the same analysis was applied to the scenario "Brazilian Company", as demonstraded in Table 25. Changes are minor, and follow the same tendencies already described for the energy consumption estimations.

By contrast, more relevant changes were found between the two scenarios applied to the "European Union Company", as demonstrated in Table 26.

Table 25: Comparison between absolute values of each impact category, considering: (a) energy production of database and (b) energy balance for 2013 for scenario "Brazilian Company".

Impact category	Unit	(a)	(b)	%
Atmospheric impacts				
Climate change	kg CO_2 eq	2.16E+03	2.16E+03	-0.05
Ozone depletion	kg CFC-11 eq	2.54E-04	2.54E-04	-0.24
Photochemical oxidant formation	kg NMVOC	1.18E+01	1.21E+01	2.75
Particulate material formation	kg PM_{10} eq	3.32E+00	3.34E+00	0.81
Resource depletion				
Terrestrial acidification	kg SO_2 eq	7.86E+00	7.98E+00	1.45
Freshwater eutrophication	kg P eq	1.38E-01	1.37E-01	-0.61
Marine eutrophication	kg N eq	4.16E-01	4.18E-01	0.33
Metal depletion	kg Fe eq	5.27E+01	5.27E+01	-0.06
Fossil depletion	kg oil eq	7.36E+02	7.39E+02	0.38
Toxicidade				
Human toxicity	kg 1,4-DB eq	2.69E+02	2.69E+02	-0.01
Terrestrial toxicity	kg 1,4-DB eq	1.86E-01	1.84E-01	-1.08
Freshwater toxicity	kg 1,4-DB eq	3.62E+00	3.60E+00	-0.37
Marine toxicity	kg 1,4-DB eq	3.94E+00	3.93E+00	-0.30

Table 26: Comparison between absolute values of each impact category, considering: (a) energy production of database and (b) energy balance for 2013 for scenario "European Company".

Impact category	Unit	(a)	(b)	%
Atmospheric impacts				
Climate change	kg CO_2 eq	6.26E+02	5.77E+02	-7.83
Ozone depletion	kg CFC-11 eq	2.98E-05	2.67E-05	-10.37
Photochemical oxidant formation	kg NMVOC	1.76E+00	1.57E+00	-10.84
Particulate material formation	kg PM_{10} eq	6.78E-01	5.60E-01	-17.37
Resource depletion				
Terrestrial acidification	kg SO_2 eq	1.99E+00	1.56E+00	-21.78
Freschwater eutrophication	kg P eq	2.89E-02	1.21E-02	-58.03
Marine eutrophication	kg N eq	7.88E-02	6.88E-02	-12.65
Metal depletion	kg Fe eq	1.30E+00	1.86E+00	43.56
Fossil depletion	kg oil eq	9.11E+01	7.53E+01	-17.35
Toxicity				
Human toxicity	kg 1,4-DB eq	4.16E+01	2.85E+01	-31.44
Terrestrial toxicity	kg 1,4-DB eq	3.26E-02	1.79E-02	-45.15
Freshwater toxicity	kg 1,4-DB eq	5.15E-01	2.87E-01	-44.35
Marine toxicity	kg 1,4-DB eq	6.01E-01	3.35E-01	-44.33

As shown, estimations for the “climate change” changed about 7%, while values of the "ozone depletion" and "photochemical oxidants formation" decreased around 10%. Estimations of the "particulate material formation" also decreased (around 17%), exactly like for the "fossil depletion". The biggest variation was observed on the "freshwater eutrophication, (58%), followed by “acidification”, 21%. Marine eutrophication also decreased (12%). The only exception was observed on the "metal depletion" estimation that increased 44%.

Just as happened to the other scenarios, all toxicity impact categories decreased, between around 30% to human toxicity and 45% (the others). This difference is caused by use of the standard 2000 scenario against the one developed for 2013. In 2000, the energy was mostly produced by thermal power units, corresponding to more than 70%. By contrast, in 2013, more than 50% of the energy was produced from renewable sources, as hydric or eolic(PorData, 2015).

4.5.3. Normalization

Normalization makes possible to estimate the magnitude of changes on each impact category, when a specific scenario is compared with a standard one. In general, this reference represents the environmental charge in a country or continent, divided by the number of habitants (Pré, 2014). The method Recipe H, used in this research, presents two metrics: “World Average” e “Europe Average”. The normalization to scenario “Brazil Estimatives” and “Brazilian Company” was calculated base on the first (Goedkoop et al., 2012). To the scenario “European Union Company”, we used the metric “Europe Average”. The result is presented in the Figure 31.

It is important highlight that Simapro software, in contrary to others, does not divide the results by a reference value, but multiply them (Bv, 2014). Due to this, the value for “human toxicity” (HT) factor is surpasses the unit.

In general, the European Company presents the minor environmental impacts, while Brazilian Company presents the highest environmental impacts. However, we should remind that Brazilian scenarios were estimated by using part of the data as the maximum and allowed values according to the national regulations. Thus, the contribution of each unit of production might be overestimated, especially the human toxicity impacts.

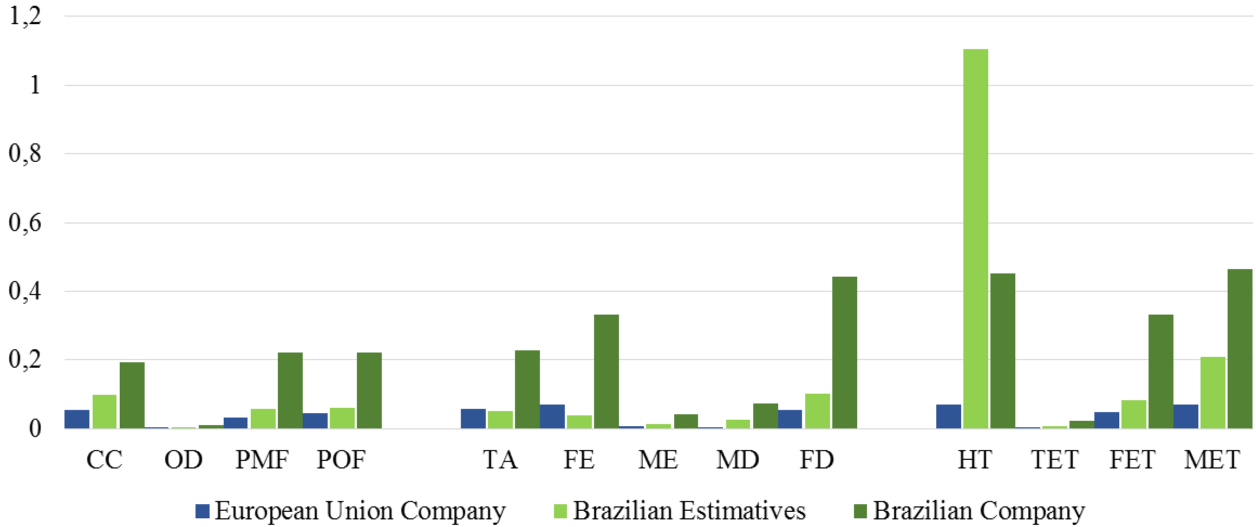

Figure 31: Impacts normalization.

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5. CONSIDERAÇÕES FINAIS

Este trabalho analisou, por meio da Avaliação de Ciclo de Vida, a produção de cimento em três diferentes cenários: uma empresa europeia (cenário “Empresa Europeia), uma empresa brasileira (cenário “Empresa Brasil”) e um cenário baseado em dados públicos e estimativas (cenário “Estimativas Brasil).

O cenário Empresa Europeia foi analisado segundo o método CML 2001 e segundo o método Recipe. Verificou-se que, apesar das diferenças metodológicas, as conclusões gerais para os impactos que podem ser comparados não se alteram: as emissões atmosféricas contribuem significativamente para quase todas as categorias de impacto, bem como a geração de eletricidade e a obtenção de combustíveis fósseis. Apesar disso, utilizando os resultados obtidos pelo método CML 2001, foi possível comparar esta análise à outras desenvolvidas para outras empresas na Europa e verificou-se que a empresa estudada apresenta desempenho ambiental satisfatório. Outras categorias de impacto referentes à depleção de recursos e toxicidade para este cenário foram estudadas segundo o método Recipe. Verificou-se que para as categorias de impacto de toxicidade, a geração de eletricidade apresenta contribuição mais expressiva que as emissões atmosféricas.

Para o cenário Estimativas Brasil, esta análise significa um primeiro passo no sentido da compreensão dos impactos associados à indústria cimenteira nacional. Os resultados encontrados com base no método Recipe vão ao encontro com a literatura em relação à emissão de CO2 e à eficiência energética do processo. É necessário considerar que o uso intensivo de combustíveis fósseis também é significante. Entretanto, por se tratar de um cenário baseado em estimativas, os transportes associados a este processo produtivo não foram considerados. Conforme demonstrado no cenário Empresa Brasil, a atividade de transporte das matérias primas é de extrema relevância para os potenciais impactos ambientais da produção de cimento.

Neste último cenário, os transportes aparecem como a atividade mais impactante associada à produção de cimento, o que se deve ao fato de que o principal modal de transportes no país é o rodoviário. Além disso, a empresa importa uma de suas principais matérias primas, e parte do transporte é realizada por caminhões, o que afeta significativamente esta análise.

Finalmente, pode-se considerar que o objetivo geral deste trabalho foi atingido, uma vez que foram levantados dados suficientes para analisar a atividade de coprocessamento no Brasil, em comparação com o praticado na União Europeia. Concluiu-se que a substituição de combustíveis fósseis por alternativos, embora represente uma alternativa interessante do ponto de vista da gestão de resíduos sólidos, só é uma alternativa ambientalmente amigável quando os impactos do transporte desses combustíveis alternativos não forem maiores que os impactos da extração e transporte dos combustíveis fósseis.

Assim, recomenda-se fazer uma verificação caso a caso da relação entre coleta, tratamento e destinação de alternos versus extração e transporte de combustíveis fósseis.

6. SUGESTÕES PARA TRABALHOS FUTUROS

- Expandir o estudo para eficiência energética e viabilidade de novas tecnologias para a empresa europeia.
- Estudar detalhadamente os processos envolvidos no desenvolvimento do estudo de ACV para o cenário Brasil e para a empresa brasileira.
- Ampliar e aprofundar o inventário baseado em dados primários para a empresa brasileira.
- Desenvolver ferramentas para melhorar a comunicação e a logística entre fornecedores de matérias primas e combustíveis alternativos e as empresas de cimento.
- Ampliar a aplicação de estudos de ACV para outros tipos de cimento e materiais cimentícios que têm como prerrogativa menor impacto ambiental para fins de comparação e mitigação de impactos associados.